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Tim O'Halloran

PRELIMINARY SUBJECT TO REVISION June 24, 1991

PROCESSES CONTROLLING SELENIUM AND OTHER CONSTITUENTS IN IRRIGATION DRAINWATER AND THEIR EFFECTS ON WILDLIFE OF THE SALTON SEA AREA, IMPERIAL COUNTY, CALIFORNIA, 1986-90

U.S. Geological Survey

Water-Resources Investigations Report 91-

U.S. Geological Survey
U.S. Fish and Wildlife Service
U.S. Bureau of Reclamation

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and I'll pass them on to Setmire. I'll send you a draft copy of the data report when its complete in a couple months.

Sorry Aug. 28th for a presentation of results doesn't look good but I'll be happy to do it some other day.

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PRELIMINARY SUBJECT TO REVISION June 24, 1991

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Sacramento, California
1991

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U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY
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Abbreviations

DW	Dry weight
WW	Wet weight
NCBP	National Contaminant Biomonitoring Program (U.S. Fish and Wildlife Service)
NWR	National Wildlife Refuge
[WA	Wildlife Area]
WMA	Wildlife Management Area
NAS	National Academy of Sciences
TSMP	Toxic Substances Monitoring Program
OC	Organochlorine ~~P~~esticides p.c.
PVC	polyvinylchloride
g/kg	gram per kilogram
mg/kg	milligram per kilogram
mg/L	milligram per liter
μg/L	microgram per liter
μg/g	microgram per gram
μg/kg	microgram per kilogram
kg/ha	kilogram per hectare
μm	micrometer
μS	microsiemen
μS/cm	microsiemen per centimeter at 25 °C
M	mole (gram-molecular weight)
ppm	part per million
ppb	part per billion
TU	tritium unit

Authors/USGS

Is there a designation WA? This be in error an earlier Volta (at one place in text was Volta

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ABSTRACT

A detailed investigation of the Salton Sea area by the U.S. Department of the Interior was completed in 1990. Overall objectives of the study were to determine the extent, magnitude, and effects of contamination associated with agricultural drainage on migratory and resident birds and their habitats and to determine the sources and exposure pathways of contaminants.

Results of the study indicate that factors controlling contaminant concentrations in subsurface drainwater in the Imperial Valley are soil characteristics, hydrology, and agricultural practices. Higher contaminant concentrations commonly were associated with clayey soils, which retard the movement of irrigation water and, thus, increase evaporative concentration.

Regression of hydrogen- and oxygen-isotope ratios in samples collected from sumps demonstrates that Colorado River water is the sole source of subsurface drainwater in the Imperial Valley. Elemental ratios of selenium to chloride indicate that selenium detected in subsurface drainwater throughout the Imperial Valley originates from the Colorado River. The selenium load discharged to the Salton Sea from the Alamo River is about 6.5 tons per year. Calculations were not made of the large volume of water entering the United States from Mexico in the New River.

Biological sampling and analysis showed that drainwater contaminants, including selenium, boron, and DDE, are accumulating in tissues of migratory and resident birds utilizing food sources in the Imperial Valley and Salton Sea. Selenium concentrations in piscivorous birds, shorebirds, and the endangered Yuma clapper rail were at levels that my be affecting reproduction. Selenium bioaccumulated in "clean" Asiatic river clams placed in a major irrigation drain during spring planting. Indigenous clams accumulated selenium in proportion to inflow of irrigation drainwater, thus showing that clams can be an excellent selenium biomonitor. Boron concentrations in migratory waterfowl and resident shorebirds were at levels that potentially could cause reduced growth in young. Waterfowl and piscivorous birds in the Imperial Valley may be experiencing reproductive impairment as a result of DDE contamination of food sources. Some of the highest concentrations were found in birds feeding in agricultural fields on invertebrates and small mammals. A total of 19 organochlorine pesticides, other than DDE and its metabolites, were found in biota. Of these, only two, toxaphene and hexachlorobenzene, were detected at levels above 1 microgram per gram, dry weight. No organochlorine pesticide residues above the National Academy of Sciences threshold of 1 microgram per gram to protect predatory (piscivorous) birds were found in fish.

INTRODUCTION

Background

State and Federal agencies, as well as private citizens, have expressed concern that contamination of the Salton Sea by agricultural drainwater is occurring and that it may be a threat to human health and to the survivability of fish and wildlife resources of the Salton Sea area. In 1986, the U.S. Department of the Interior began an investigation of irrigation drainage in the Salton Sea area. The initial phase of the investigation, a reconnaissance, was completed in 1988. Results of the reconnaissance, reported by Setmire and others (1990), indicated that selenium, boron, and DDT metabolites are present in elevated levels that could cause phyiological harm to resident wildlife and fish of the Salton Sea National Wildlife Refuge (NWR).

During the reconnaissance study, elevated levels of selenium were detected in samples of water and bottom sediment collected in the Imperial Valley. The highest measured selenium concentrations were from irrigation drainage, which consists of a concentrate from the percolation of irrigation water through a shallow (usually about 6 ft) soil column. Of bottom-sediment samples collected in the study area, those from the Salton Sea near the mouth of the Alamo River (the major tributary to the sea) had the highest concentrations. These results indicated the need for a more detailed investigation in the Imperial Valley.

Purpose and Scope

This report presents the results of a detailed investigation of the Salton Sea area completed by the U.S. Department of the Interior in 1990. The detailed investigation was a joint effort conducted by scientists from the U.S. Geological Survey and the U.S. Fish and Wildlife Service. The U.S. Geological Survey was responsible for determining the hydrologic and geochemical factors affecting concentrations of irrigation-induced contaminants, particularly selenium, and the U.S. Fish and Wildlife Service was responsible for identifying pathways of contaminant accumulation in biota. The results of the detailed investigation are to serve as the basis for possible future remediation efforts under the direction of the U.S. Bureau of Reclamation.

This report contains analysis and interpretation of the data collected for the detailed study. Summary tables are provided as needed to support the text. Because of the volume of biological, water, and sediment data collected during this intensive study, the actual data tables have not been included. A separate data report, U.S. Geological Survey Open-File Report 91-XXX, has been released to provide this information. The soils data for the 15 fields sampled in the Imperial Valley and analyzed by the USGS Geologic Division laboratory in Denver, Colorado, will be presented in a separate report.

The general goals of the Department of the Interior study were to: (1) determine the geographical extent and severity of existing and potential irrigation-induced water-quality problems, and (2) provide the scientific understanding needed for development of reasonable alternatives to mitigate or resolve identified problems. Within this context, the overall objectives of the detailed study were to determine the extent, magnitude, and effects of contaminants associated with agricultural drainage on migratory birds and their habitats and, where effects are documented, to determine the sources and exposure pathways of contaminants.

Specific objectives were developed for the detailed study, on the basis of results of the reconnaissance investigation, using the general goals as a framework. Included in this development process were the selecting and prioritizing of biota collections from the Salton Sea NWR and adjacent areas. High priorities were assigned to organisms most likely, because of their ecological niche, to show effects of contaminant exposure; the potential exposure of endangered species to contaminants also was considered.

The specific objectives that were developed for the detailed study were to:

1. Determine the source and movement of selenium and boron in the agricultural system of the Imperial Valley and the processes affecting concentrations of these elements.

2. Determine if selenium and (or) other contaminants associated with agricultural drainwater are accumulating in selected migratory bird species utilizing the Salton Sea NWR as a wintering area.

3. Determine if any drainwater contaminants have caused any adverse chronic, or sublethal effects on resident birds that nest in the Salton Sea area or if there is the potential for adverse effects on reproductive success of migratory birds utilizing the Salton Sea as a wintering area.

4. Determine the bioaccumulation of selenium and (or) other drainwater contaminants in aquatic food-chain organisms important to fish and to migratory and resident birds.

5. Determine if selenium and (or) other contaminants could be bioaccumulated by transplanted freshwater clams exposed to drainwater discharges. If so, determine seasonal variation in bioaccumulation of contaminants in the transplanted clams.

Description of Study Area

FIGURE 1 near here

The study area for the reconnaissance investigation consisted of the major agricultural areas of the Coachella and Imperial V .eys (fig. 1). Because wildlife refuges are located in the Imperial Valley, and because of limited resources, this more detailed study focused primarily on the southern end of the Salton Sea and on irrigation drainage originating in the Imperial Valley. See Setmire and others (1990) for a detailed discussion of the geology and history of the Salton Sea area.

Figure 1. Location of study area.

Ecology of Salton Sea Area

The Salton Sea is, in essence, a manmade body of water having a largely manmade ecosystem (figs. 2 and 3). Most of the natural world is composed of complex and dynamic food webs that have developed over a very long time period; by contrast, the relatively recent formation of California's largest inland body of water and the subsequent introductions of numerous species that were not native to the area, have resulted in a relatively simplified regional ecology. Salton Sea food webs are short and lack diversity (Walker, 1961). Because of this simplicity, any changes in lower trophic levels have the potential to dramatically alter the populations of top predators, such as piscivorous birds.

FIGURE 2 & 3 near here

The Salton Sea lies within the Cahuilla Basin, or Salton Sink, an actively spreading rift valley that is below sea level. Fossils have been found that indicate at least short durations of saltwater inundation, implying that the basin was a continuation of the Gulf of California prior to the formation of the Colorado River delta (Walker, 1961). Formation of the delta separated the valley from the Gulf and created a closed basin containing the Imperial Valley. In geologically recent times, the Colorado River's flow periodically has emptied into the Imperial Valley for various amounts of time. The volume of shells left by freshwater mollusks and the deposits of calcium carbonate in the form of travertine or calcareous tufa show that Lake Cahuilla, the most recent (about 1,500 years before the present) of the inland seas, was not saline (Walker, 1961).

Figure 2. The Salton Sea. Looking east from south end of the sea toward the Chocolate Mountains.

Figure 3. The Salton Sea. Looking west across the north end of the sea toward Obsidian Butte.

Uncontrolled flooding during 1905 diverted the Colorado River from its former course into the Gulf of California, into the Cahuilla Basin and created the present Salton Sea. Since 1907, water has entered the sea through a system of controlled drains that are influenced by irrigation practices in the agriculturally rich Coachella and Imperial Valleys. The sea acts as a sump for irrigation-water drainage, and although an estimated 1,300,000 acre-ft of water drains into it each year, annual evaporation of about 2 m maintains the surface of the Salton Sea at a fairly stable level, with its highest elevation in spring and its lowest in autumn (Setmire and others, 1990). Currently, the water level of the sea is about 226 ft below sea level, and the sea's greatest depth is about 50 ft.

Salinity of the Salton Sea is as great as 44 parts per thousand, about 25 percent greater than that of the Pacific Ocean (Hagar & Garcia, 1988). Because it is within a closed basin having low rainfall and high evaporation, the sea has tended to become increasingly saline (U.S. Department of the Interior and the Resources Agency of California, 1974). The sea is less saline at the mouths of most major drains, and this freshwater influence is reflected by the species composition at these tributaries. Another ecological influence is the effect of solar radiation--which creates extremes between surface and bottom temperatures and, in turn, affects the dissolved-oxygen content of the water (Walker, 1961). Oxygen becomes increasingly less soluble in higher salinities (Hagar and Garcia, 1988). Although dissolved-oxygen saturation is affected by temperature, low dissolved-oxygen concentrations result from high productivity (eutrophication), thermal stratification, and wind-induced resuspension of anaerobic bottom sediments. As salinity increases, organisms become more susceptible to, and more likely to succumb to, temperature stress (Hagar & Garcia, 1988). In addition, temperature and salinity may interact with factors such as parasitism (Moles & Pella, 1984) and concentrations of toxic substances (Bryant and others, 1984) to affect all life in the Salton Sea.

Studies of dissolved oxygen in the Salton Sea have shown great diurnal changes in the oxygen content of nearshore water. Dissolved oxygen was present in high concentrations throughout the water column during winter, but often was absent at the sea bottom on windless summer days (Walker, 1961). This affects the seasonal abundance of benthic organisms, along with species dependent on those organisms as food. During the eventual mixing that follows oxygen depletion at the sea bottom, the dissolved-oxygen concentration at the water's surface temporarily can be lowered below the minimum level necessary to maintain many forms of life in the sea (Walker, 1961). In addition, high concentrations of sulfide and ammonia present at the bottom during the summer are mixed into surface waters. This results in annual fish kills, which serve to feed thousands of gulls, herons, pelicans, and other wildlife such as raccoons.

There are several relatively simple food chains operating at the Salton Sea. In the sea itself, the only organisms capable of producing food from sunlight and nutrients are phytoplankton and macroscopic algae (Walker, 1961). These foods are eaten by animals and used for growth, maintenance, or to provide energy. Food that is oxidized for energy is broken down into simpler molecular components, which become available for re-use by plants; this process is called cycling. There is an energy loss at each step of the food chain because each animal in the chain passes on to its successor only a part of the energy from the food that it has consumed (Ricklefs, 1973). Perhaps the two most prominent food chains in the Salton Sea are (1) phytoplankton -> zooplankton -> detritus -> pileworm -> forage fish -> predatory fish -> piscivorous birds and (2) a shorter chain: phytoplankton -> zooplankton -> detritus -> pileworm -> water bird. A typical drainwater ecosystem might be: phytoplankton -> zooplankton -> aquatic insects -> forage fish -> water birds and turtles. Many migratory waterfowl species feed primarily on emergent and submergent vegetation; this represents the shortest food chain in the Salton Sea ecosystem. Ultimately, some of the Salton Sea's waterfowl and gamefish progress farther through the food chain when they are consumed by humans. The basic ecology of the Salton Sea and relations among organisms of different trophic levels are shown in figures 4 and 5.

fig 4 & 5 near here

Primary productivity in the Salton Sea is accomplished by phytoplankton, which absorb energy from sunlight and photosynthesize it to produce carbohydrates, proteins, and fats from carbon dioxide, bicarbonate, nitrate, ammonia, and phosphate that are dissolved in the sea (Walker, 1961). In the Salton Sea, phytoplankton is represented by several pennate diatom species and by dinoflagellates.

Figure 4. Trophic relations among organisms of the Salton Sea.

Figure 5. Trophic relations among organisms of rivers and drains.

Diatoms are found both offshore and near shore; dinoflagellates normally are found near shore and are subject to local blooms. Because of their large size and numbers, the most important phytoplankton in the Salton Sea include the genera *Nitzschia*, *Cyclotella*, *Glenodinium*, and *Exuviella*. Populations are relatively small during the summer, but the phytoplankton are present throughout the year (Walker, 1961). Due to turbidity and the volume of planktonic life in the sea, it is estimated that only the first meter of the water column receives enough light to support photosynthesis (Walker, 1961). In addition to microscopic phytoplankton, macroscopic green algae exist in both the freshwater drainages emptying into the sea--and some species of green algae (such as *Enteromorpha* sp.) exist in the sea itself. Also, blue-green algae species grow on the bottom of the sea in shallow water or on pilings and buoys (Walker, 1961). Because benthic plants are limited to a very narrow fringe around the periphery of the sea, they produce less biomass than do phytoplankton (Sumich, 1979).

Invertebrate life in the Salton Sea is represented by various protozoans, rotifers, bryozoans, nematodes, annelids, and arthropods; the most important of these in the local food chains are the annelids and arthropods. Various species of mollusks are present only in freshwater tributaries. Protozoans and nematodes occur primarily in the algal mats and in decaying organic matter and are utilized to some extent by organisms that feed on the sea bottom. The more-planktonic rotifers provide food to filter-feeding animals in the sea. The moss-like bryozoans are believed to be insignificant in the food cycle (Walker, 1961).

Amphipods and pileworms (*Nereis succinea*) represent perhaps the most critical link in the food chain because these are the only animals in the sea that convert detritus into food for other organisms (Walker, 1961). Amphipods are present in both freshwater and saltwater ecosystems at the Salton Sea, where they exist primarily as benthic organisms living in bottom debris, in macroscopic algae, and among sessile animals (Villee and others, 1973). Many amphipods burrow into sand or mud, and some are tube dwellers. The amphipods present at the Salton Sea are omnivores and scavengers, and they in turn are eaten by various fish and bird species.

The pileworm, which was introduced to the sea about 1930 and has been abundant since about 1935 (Walker, 1961), is the principal detritus-feeding animal in the Salton Sea. Pileworms are restricted to fine sand and silt material, where they spend most of their lives in burrows or among masses of barnacles (Kuhl & Oglesby, 1979). Pileworms are most abundant in the bottom sediments at water depths of 5 to 8 m but seasonally are found throughout the sea at every depth (Walker, 1961). During the summer, pileworms are not able to survive below depths of 9 m because of the lack of oxygen (Walker, 1961). Mature pileworms leave their burrows at night and swim to the surface to spawn. Although spawning occurs throughout the year, it peaks during spring and fall (Kuhl & Oglesby, 1979). The eggs and larvae are planktonic and all stages of the pileworm are extremely important to the Salton Sea food chains. Fish in the Salton Sea are largely dependent on the pileworm, whose food value is high because pileworms have a greater proportion of proteins and fats (although fewer carbohydrates) in comparison with mollusks or crustaceans (Zenkevich, 1951).

The barnacle *Balanus amphitrite* was first observed at the Salton Sea in 1944 (Walker, 1961). Barnacles in the sea are limited by the number of solid surfaces upon which to attach; most barnacles are found near shore where there are more surface areas for attachment. There are two abundance peaks in the planktonic population--one occurs in spring and another in autumn. The planktonic population is low during winter. Although not vitally important to the food chain, the great numbers and the rapid growth of barnacles in the Salton Sea make them significant (Walker 1961). Adult barnacles in the sea are eaten occasionally by fish, and the planktonic larvae are fed on by filter-feeding organisms and to a limited extent by young fish. Barnacles also are eaten by wintering waterfowl such as ruddy ducks (*Oxyura jamaicensis*) and scaup (*Aythya* sp.). Perhaps more importantly, barnacle shells are washed up and deposited on some of the Salton Sea beaches where they are crushed by wave action into a coarse sand. These "barnacle bars" serve to impede some freshwater drainflows into the sea and in some places create ponds of water having a different salinity than the sea itself. These ponds are utilized extensively as feeding areas by shorebirds and other wildlife.

The reproductive peaks of both pileworms and barnacles are most prevalent during the spring and autumn, making plankton fairly rich and abundant during those seasons. The total numbers of zooplankton, however, are greatest during summer when rotifers and copepods appear (Walker, 1961). The rotifer, *Brachionus plicatilis*, is the most numerous animal in the summer plankton of the Salton Sea, but it does not seem to be a direct source of food for any animal in the sea (Walker, 1961). The copepod, *Cyclops dimorphus*, is present only during the warmest part of the year (Walker, 1961). Copepods are an important link in the food chain of the Salton Sea because they feed on phytoplankton and are then eaten by young fish. Dead rotifers and copepods add to the organic matter (detritus) on the sea bottom, where they are fed on by bacteria and pileworms.

The Whitewater River, Alamo River, New River, and numerous smaller tributaries to the Salton Sea act to drain agricultural lands from both the Imperial and Coachella Valleys. Two "natural" tributaries (that is, containing no agricultural drainwater) are San Felipe Creek and Salt Creek. All agricultural drains contain an ecosystem composed largely of introduced organisms, including common reed (*Phragmites communis*), saltcedar (*Tamarix* sp.), the Asiatic river clam (*Corbicula fluminea*), the crayfish (*Procambraus clarkii*), and numerous introduced fish species. Freshwater drains and ponds contain ample aquatic invertebrate life, notably waterboatman (*Corixa* sp.), which also is found in the saltwater-freshwater interface where the drains and sea meet. Adult waterboatmen can fly and rapidly colonize new bodies of water where they swim and feed on algae and minute submerged food particles (Milne & Milne, 1980). Waterboatmen are preyed on by numerous fish and bird species, such as the black-necked stilt (*Himantopus mexicanus*). Agricultural fields, when irrigated, flood out terrestrial insects such as crickets (*Gryllus* sp.) and earthworms, making them readily available to large numbers of cattle egrets (*Bubulcus ibis*), white-faced ibis (*Plegadis chihi*), long-billed curlews (*Numenius americanus*), and other birds that forage among the crops throughout the year.

Two introduced amphibians and reptiles that are important in the region's food chains include the bullfrog (*Rana catesbeiana*) and the spiny softshelled turtle (*Trionyx spiniferus*). Both species are common in the sea's freshwater inlets where they serve largely as predators. Bullfrogs feed mostly on aquatic invertebrates living in the drains, and they are fed on by fish, herons, egrets, bitterns, skunks (*Mephitis* sp.), raccoons, and humans. The highly aquatic spiny softshelled turtle is abundant in freshwater drains where it feeds on various invertebrates, frogs, and fish, or scavenges on lifeless organisms (Stebbins, 1985). Young turtles become prey to various birds and mammals, but adult softshelled turtles are taken by few predators other than humans.

Although the federally endangered desert pupfish (*Cyprinodon macularis*), is the only fish native to the Salton Sea area, currently at least 15 introduced fish species inhabit the sea and its associated drains. The chief gamefish of the sea is the orangemouth corvina (*Cynoscion xanthulus*), which has supported a substantial sport fishery (Walker, 1961). This species occupies the top of the aquatic food chain and feeds on tilapia (*Tilapia mossambica*), longjaw mudsucker (*Gillichthys mirabilis*), bairdiella (*Bairdiella icistius*), sargo (*Anisotremus davidsoni*), and threadfin shad (*Dorosoma petenense*), all of which are important forage species. These forage fish in turn feed on plankton--including fish eggs, copepods, barnacle larvae, and amphipods--but primarily on pileworms (Walker, 1961). Pileworms are the staple food item for all but very young fish. The most important limiting factor for some fish species in the sea may be the scarcity of pileworms during summer and early fall (Walker, 1961). The Salton Sea currently is too saline to allow successful spawning by many of the resident fish species (Lasker and others, 1972, 1975); however, some recruitment probably comes from fish entering the sea from freshwater inlets and the less-saline drain outlets at the confluence with the sea. Freshwater drains contain large numbers of tilapia (*Tilipia zilli*), carp (*Cyprinus carpa*), mosquitofish (*Gambusia affinis*), sailfin molly (*Poecilia latipinna*), longjaw mudsucker, and red shiner (*Notropis umbratilis*), which are important forage for larger fish, predatory birds, and numerous other wildlife species.

Although corvina, sargo, and bairdiella eggs and larvae currently can tolerate the salinity levels in the sea (California Department of Fish and Game, 1987), there is some indication that production of these species is declining. In addition, tilapia in the sea experience significant population fluctuations as a result of low winter temperatures (Hagar & Garcia, 1988). However, the reproductive potential of the Salton Sea fishery is extraordinary. Numbers are traditionally held in balance through fish mortalities that occur each year during summer or early autumn as a result of food depletion, lack of oxygen, or a combination of both factors (Walker, 1961).

Fig 6 & 7 near here

The Salton Sea supports an unusual diversity and abundance of birds: more than 375 species utilizing the various habitats available on or adjacent to the sea. The sea's abundant supply of invertebrate life directly supports large numbers of wintering waterfowl, grebes, and shorebirds (figs. 6 and 7). Cumulative numbers of northern pintail (*Anas acuta*), northern shoveler (*Anas clypeata*), ruddy duck, and other waterfowl have exceeded 125,000 in recent years; the number of eared grebes (*Podiceps caspicus*) has been as high as 300,000. Fish produced in the sea or its freshwater inlets provide abundant food for predatory species such as pelicans, cormorants, herons, egrets, terns, and osprey. As many as 5,000 endangered brown pelicans (*Pelecanus occidentalis*) occasionally spend the summer on the Salton Sea, as recently as 1988, as many as 2,000 herons, cormorants, and egrets were surveyed nesting at the southeast end of the sea alone. Bird species that scavenge along the shoreline of the Salton Sea are represented primarily by turkey vultures (*Cathartes aura*) and as many as 17 species of gulls. The Salton Sea regularly supports such western avian rarities as the brown booby (*Sula leucogaster*), roseate spoonbill (*Ajaja ajaja*), wood stork (*Mycteria americana*), and fulvous whistling duck (*Dendrocygna bicolor*). The sea is one of the few nesting sites in the United States for gull-billed terns (*Gelochelidon nilotica*) and is one of only two nesting sites in the Western States for black skimmers (*Rynchops nigra*). Many of the wildlife attracted to the sea become prey for raptorial bird species such as the peregrine falcon (*Falco peregrinus*) and the bald eagle (*Haliaeetus leucocephalus*), both of which are listed as Federally endangered species. Another endangered species, the Yuma clapper rail (*Rallus longirostris yumaiensis*) is dependent on cattail wetlands and associated invertebrate foods made available by freshwater drains into the Salton Sea. Shorebirds, with peak numbers of more than 100,000, utilize Salton Sea habitats during winter and migration periods (Page and others, 1990), and shorebird species such as the black-necked stilt are abundant breeders at the Salton Sea.

Mammals that are important to the Salton Sea ecosystem include herbivores, insectivores, and carnivores. Several rodent species exist in terrestrial habitats, where they provide important foods for raptors and other predators. During winter months, rodents become an important food item for herons and egrets. Muskrats (*Ondatra zibethica*) are present in freshwater tributaries, where their feeding and burrowing activities help maintain marsh habitats for various other species. At least 12 kinds of bats utilize the Salton Sea area and ingest very large numbers of aerial insects produced in the Imperial Valley. Coyotes (*Canis latrans*), raccoons, and striped skunks act both as predators and scavengers (Ingles, 1965), transferring energy farther through the food chain. Finally, humans exert extraordinary influence on all the existing habitats and represent the final trophic level in some Salton Sea food chains.

The creation of any new habitat invites a host of invading species that are quick to exploit available resources (Ricklefs, 1977). Not all species in a community are not equally abundant. Organisms with high reproductive potentials tend to make the most complete use of the available food by varying their population size to match the food supply (Walker, 1961). Pileworms exemplify this potential in the Salton Sea. Organisms of lower reproductive potential cannot adjust their population size as rapidly to food fluctuations and tend to stabilize near the low point of their food supply (Walker, 1961). Such low-point stabilization currently is shown at the Salton Sea by fish-eating species such as cormorants, herons, and egrets, which virtually have ceased nesting, perhaps in response to a large-scale tilapia dieoff or possibly to the effects of contaminants. The Salton Sea is a very productive body of water and produces, per unit volume, more phytoplankton than does fertile coastal ocean water (Walker, 1961). Existing food chains are limited by the interactions between salinity and temperature as well as by the influences of these interactions on dissolved oxygen content (Hagar & Garcia, 1988). The tributaries that carry drainwater from agricultural fields in both the Imperial and Coachella Valleys into the Salton Sea have the potential to contribute various contaminants into the ecosystem at most trophic levels.

Previous Investigations

Setmire and others (1990) collected water, bottom sediment, and biota samples during 1986-87 in the Salton Sea area to determine concentrations of trace elements and pesticides as part of the Department of Interior Irrigation Drainage Program. Results of this reconnaissance-level investigation indicated that selenium, boron, and DDT metabolites are the major contaminants of concern.

Elevated concentrations of selenium in water were restricted to tile-drain-effluent. The highest selenium concentration of 300 μg/L was detected in a tile-drain sample, and the lowest concentration of 1 μg/L was detected in a composite sample of Salton Sea water. The median selenium concentration in 12 samples was 19 μg/L. In contrast to the pattern for water, the highest bottom-sediment concentration of 3.3 mg/kg was in a composite sample from the Salton Sea.

In fish from the Salton Sea, selenium levels ranged from 3.5 to 20 μg/g, dry weight (DW), for tilapia and corvina: the mean concentration, 10.5 μg/g DW, exceeds the health advisory level of 8 μg/g DW for human consumption of fish. The levels of selenium observed in samples of birds have been linked to reproductive problems at other drainwater study sites. Selenium was detected at concentrations as high as 27 and 42 μg/g in livers of black-necked stilt and cormorant. However, the biological effects of selenium at these concentrations in the Salton Sea area were not documented.

Boron concentrations also were elevated in tile-drain effluent and in the Salton Sea. The median concentration in 12 water samples was 1,750 μg/L (Setmire and others, 1990). The highest concentration of 11,000 μg/L was in a composite sample from the Salton Sea. Trifolium drain 1, which discharges directly to the Salton Sea, had a boron concentration of 1,300 μg/L, and the Alamo River at the outlet to the Salton Sea had a concentration of 680 μg/L. Boron concentration in subsurface drainwater (eight samples) ranged from 200 to 3,400 μg/L.

The highest levels of boron in biota were found in plant samples. A sago pondweed sample had a boron concentration of 370 μg/g. Levels of boron in the rooted aquatic plants bulrush and sorrel ranged from 40 to 130 μg/g (mean 68.6 μg/g). Samples from the three drainwater-impacted sites were higher (61 to 130 μg/g; mean 81.3 μg/g) than the control sites (40 to 48 μg/g; mean 43.0 μg/g). Smith and Anders (1989) have found adverse dietary effects on waterfowl at concentrations within this range. However, the biological effects of boron at these concentrations at the Salton Sea were not observed.

Organochlorine pesticide residues were detected in bottom sediment at concentrations approaching those found in 1977 (Eccles, 1978). Although no DDT was detected in the 1986-87 reconnaissance investigation, its metabolites DDD and DDE were found at concentrations as high as 64 μg/kg (DDE) in bottom sediments of the Alamo River at its outlet, and 24 μg/kg (DDD) in bottom sediment of the New River at the international boundary.

Preliminary evaluation of the DDT and its metabolites in biota did not indicate substantial differences from results of other studies; however, interpretation was deferred until data from additional samples were collected in this detailed investigation.

Saiki (1990) collected a total of 21 composite samples of 4 different fish species from the Salton Sea for analysis of trace-element concentrations. The species collected were orangemouth corvina (*Cynoscion xanthulus*), bairdiella (*Bairdiella icistia*), sargo (*Anisotremus dividsoni*), and Mozambique tilapia (*Tilapia mossambica*), which represent the major recreational fishery of the Salton Sea as well as a significant food source for piscivorous birds. Concentrations of 12 elements were detected, but only selenium was elevated in comparison with levels measured in either the flesh or whole body of saltwater fishes from other studies. However, the threshold concentration in tissues for which selenium is toxic to saltwater fishes remains unknown. Boron concentrations in fish from the Salton Sea were comparable to those found in Setmire and others (1990).

Cook and Bruland (1987) and McCleneghan and others (1981) studied the occurrence and distribution of inorganic and organic selenium species in the Kesterson Reservoir, San Joaquin River, and the Salton Sea. At sites in the Salton Sea, they found a strong density gradient that resulted in anoxic conditions and the presence of hydrogen sulfide below 6 m. Water analyses indicated that 58 to 81 percent of the total selenium was in the -II or 0 oxidation state. Selenite (Se+IV) represented 33 percent of the total selenium in the oxic surface waters but less than 1 percent of the total selenium in anoxic waters. Selenate, the thermodynamically stable form in oxic water, was not detected. Organic selenides represented 42 to 74 percent of the residual selenium in the -II or 0 oxidation state, with the proportion increasing with depth.

In 1980, catfish collected from the Alamo and New Rivers as part of California's Toxic Substances Monitoring Program had concentrations of total DDT in excess of National Academy of Sciences (1973) guidelines (1.0 mg/kg WW, whole fish, in freshwater systems) (McCleneghan and others, 1981). Technical DDT, endrin, and HCB (hexachlorobenzene) also were found at levels of concern in fish collected within the Imperial Valley.

Matsui (1989) found significant recent decreases in the number of eggs and larvae for bairdiella and sargo. Also documented in this same study were deformities in ichthyoplankton that were attributed to unknown contaminants.

Mora and others (1987) investigated the seasonal variation of body condition and organochlorines in ducks from California and Mexico in 1981-82 and found some of the highest DDT and DDE concentrations in pintails collected from the Salton Sea NWR. These levels were significantly higher than levels found in the Lower Klamath NWR and were comparable to those observed at the south (high level) end of a north-to-south gradient observed in waterfowl in California by Ohlendorf and Miller (1984). In 1981, Ohlendorf and Miller (1984) found the highest levels of DDT and DDE in pintails collected from Imperial Valley--in comparison with Klamath Basin, Sacramento Valley, Sacramento/San Joaquin delta, and San Joaquin Valley. Other contaminants, such as dieldrin, PCB, and HCB, also were found in higher concentrations in Imperial Valley waterfowl. Concentrations of polychlorinated biphenyls (PCB's) and HCB in pintails and shovelers were at levels not known to have any effect on survival or reproduction. However, further sampling was recommended for Imperial Valley to determine if DDE concentrations were at potentially harmful levels.

Ohlendorf and Marois (1990) found elevated levels of DDE in great egret (geometric mean 24 μg/g WW) and black-crowned night heron eggs (geometric mean 8.62 μg/g WW) collected at Salton Sea in 1985. The mean DDE residues for night heron eggs from Salton Sea were significantly higher than those for Blair Island, Kesterson, and Volta. Seventy percent of the night heron eggs collected from Salton Sea exceeded 8 μg/g WW, which is the level known to cause decreased reproductive success in the species. Mean selenium concentration in Salton Sea night herons was higher than for other sites, but it was below concentrations associated with reproductive effects in night herons.

Researchers at the Lawrence Livermore Laboratory previously found high selenium concentrations from wintering waterfowl in the Imperial Valley (Koranda and others, 1979). Mean concentrations (DW) were 15 μg/g in green-winged teal, 15.6 μg/g in shovelers, 11.2 μg/g in pintails, and 49.5 μg/g in ruddy ducks.

On the basis of prey-item and band-recovery data, black-crowned night herons (Henny and others, 1984) and white-faced ibis (Henny and Herron, 1989) wintering in the Imperial Valley are experiencing decreased reproductive success at their (more northerly) breeding grounds. These studies concluded that DDE accumulation on wintering grounds was the probable source of their reproductive problems.

Development of Sampling Methodology

This section presents the working hypothesis for the selenium pathway that was used in developing the sampling methodology. Colorado River water, imported by the All-American Canal to the Imperial Valley for irrigation, contains 1 to 2 μg/L of selenium. This irrigation water is delivered to 160-acre field plots by a 1,675-mile network of canals distributed throughout Imperial Valley. Water applied to the head of the field percolates through the soil and flows to subsurface drains. The flow rate of water that reaches the drains and is discharged from the sumps varies and is dependent on the quality and timing of irrigation, on soil characteristics, and on spacing of subsurface drains. Part of the water that is applied to fields is lost by evapotranspiration; part (tailwater) runs off directly from the field to the drainage ditch; and part remains in the soil and becomes concentrated in soluble salts. Thus, irrigation in an arid environment results in an accumulation of salts in the root zone of the field or in a concentrating of soluble salts in solution. These salts and concentrated water mix to greater or lesser degrees with water from trench flow, with recently applied irrigation water, or with regional ground water and flow to subsurface drains. Selenium, along with other soluble salts in irrigation water, is concentrated in drainwater. This drainwater is collected in sumps and is discharged to drainage ditches that empty into either the New River or the Alamo River. Eventually, the drainwater empties into the Salton Sea at the delta areas of the New and Alamo Rivers or into major drains (Trifolium and Vail) that discharge directly to the Salton Sea.

In the delta areas of the New and Alamo Rivers and the major drains that discharge directly to the Salton Sea, selenium is removed from the water by selenate-respiring bacteria in the shallow anaerobic sediments. These bacteria reduce the selenate in the inflowing water to elemental selenium. Uptake of the elemental selenium by benthic organisms, particularly the pileworm, then serves as the basis for a detrital food chain in the Salton Sea (fig. 8). The food chain begins as pileworms are consumed by forage fish such as bairdiella, which are then consumed by piscivorous birds such as the federally endangered California brown pelican. This transferral of selenium between each of these trophic levels results in bioaccumulation and potentially in biomagnification.

GURE 8
here

Bioaccumulation is the accumulation of a chemical such as selenium in tissues of an organism at a concentration that is substantially higher than that in the environment in which the organism exists (Tinsley, 1979). If tissue concentrations of a bioaccumulated constituent increase in a food chain as the constituent passes from one trophic level to another, then biomagnification is said to occur.

The biomagnification of selenium in aquatic food chains has been documented in a recent study (Lemly and Smith, 1987), but it has been questioned by others (Kay, 1984). However, it is clear that selenium concentration in animal tissue tends to reflect dietary le els, particularly when the selenium is an organic form rather then the inorganic selenite or selenate (Sharma and Singh, 1983). Selenium concentrations in aquatic ecosystems are 2 to 6 times greater in producers (phytoplankton, algae, and vascular plants) than in the lower consumers (such as invertebrates and forage fish) (Lemly and Smith, 1987). It also should be noted that estuarine and marine organisms usually contain higher concentrations of selenium than do freshwater or terrestrial species (Eisler, 1985). This may be an important consideration in the Salton Sea.

Biomagnification is important because it can cause top-level consumers, such as piscivorous birds, to receive toxic selenium doses in the diet even though concentrations in water may be low (Lemly and Smith, 1987). Equally as important is the risk of toxicity through the detrital food pathway, which will continue despite a loss of selenium from the water column as long as contaminated sediments are present, such as in the Salton Sea. DDT contamination in sediments is not a direct consequence of irrigation drainage but of historical usage, soil erosion, and sediment transport.

SAMPLE COLLECTION AND ANALYSIS

Selection of Sampling Sites

Water and Bottom Sediments

Table 1 near here

Fig. 9 near here

Sites for the May 1988 sampling of subsurface irrigation drainwater (table 1) were selected using, as a template, the list of 119 sites sampled in May 1986 by the California Regional Water Quality Control Board (fig. 9). As many of the same sites as could be located were resampled. Several sites from the earlier sampling could not be located and replacement sites were chosen from an irrigation and drainage book provided by the Imperial Irrigation District (IID). Areal coverage was the primary criterion for selection of these new sites.

Soil-sampling sites and sites for monthly monitoring of variation in subsurface drainwater were selected from the May 1988 sampling sites. Selection was made in consultation with Imperial Irrigation District for sites that represent a range of moderate-to-high selenium concentrations and provide areal coverage of the Imperial Valley. From this evaluation, 15 fields were selected. For the soil collection, 18 cores were taken from each field. Sites within the field were located at the head of the field where irrigation water is applied, at the center, and at the tail where the discharge sump is located. (See "Physical Characteristics of Fields" section.) At each of these areas, samples at 3 and 6 ft below the surface were collected at three points: (1) adjacent to the subsurface drain, (2) at the midpoint between the subsurface drains, and (3) midway between the midpoint and the subsurface drain (that is, one-fourth the distance between the drains). The sumps from these 15 fields also were sampled monthly for the investigation of time-series variation in concentrations of selected constituents.

Figure 9. Subsurface-drainwater and surface-water sampling sites in the study area.

From the 15 soil-sample sites, 3 sites were selected for installation of multiple-depth wells and lysimeters to discern regional patterns in ground water. Geographic representation was the main criterion used for selection of these three sites. A site was selected in each of the northern, middle, and southern parts of the Imperial Valley. Sites are designated by the IID sump that drains the field. Because IID owns and maintains access roads to fields and sumps in the Imperial Valley, the wells and lysimeters were installed adjacent to these roads. This limited ground-water investigation, which was not part of the original Department of the Interior investigation, was performed in cooperation with the California Regional Water Quality Control Board, Region VII, which has jurisdiction over the Coachella and Imperial Valleys.

The northern well and lysimeter site, S-417 (at site 8 in fig. 9), is about 4 mi east of the Salton Sea in an area where geothermal development is prevalent. The downgradient corner of the field, near the outlet sump, was selected for the well installation. Several problems were encountered in locating the wells and lysimeters. The first was insufficient space for the drill rig and tender on the south side of the drainage ditch. Because of this limitation, the wells were placed on the north side of the ditch. Water quality in these wells is influenced by connate water, water from the field, and also by water in the drainage ditch and by water in commercial fish ponds (filled with Colorado River water) near the wells. Because no drilling mud was needed for lysimeter holes, the lysimeters were placed on the south side of the drainage ditch, as close to the tail of the field as possible without interfering with farming operations. The sump for this field is located on the east side of the field, with the subsurface drainpipes to the sump going under the ditch.

The middle well and lysimeter site, S-154 (at site 50 in fig. 9), is northeast of El Centro in an area that once (through the early 1900's) was Mesquite Lake. The lysimeters were located adjacent to sump 154 in the southwest corner of the field. Again, because of space limitations and access, the wells were located south of the sump on the other side of an east-to-west drainage ditch. Another ditch, oriented in a north-to-south direction, is immediately west of the field. Water quality in the lysimeters is influenced primarily by the field and the drainage ditch. The wells are influenced by the field, the drainage ditch, and also by fish farms located east of the north-to-south ditch.

The southern well and lysimeter site, S-371 (at site 98 in fig. 9), is southeast of El Centro. The lysimeters were located adjacent to sump S-371 in the northeast corner of the field. East of the field is a drainage ditch, oriented north-to-south, to which the sump discharges. The wells were located across from the sump east of the drainage ditch in an area between the ditch and an irrigation canal. During drilling of the lysimeter holes, the sides of the holes kept caving in because of the coarseness of the soil and a high water table. Because the lysimeters are at the downgradient corner of the field, water-quality samples collected from the lysimeters are influenced by tailwater runoff as well as by subsurface drainage from the field. Water quality in the wells is influenced by the fields, but also by the drainage ditch and the canal.

Site selection for the Alamo River delta sampling was made in the field. Beginning in the Alamo River at Garst Road, immediately upstream of the Salton Sea, measurements of specific conductance and other field constituents and properties initially were made about every 500 ft. Sites were located on a USGS quadrangle map using Loran C coordinates, the topography of the surrounding land, and prominent local features. Measurements and sampling were performed at increasingly shorter intervals near the mouth of the Alamo River. Sample and measurement sites also were selected to determine any areal distribution of selenium in the bottom sediments and associated changes in the water column as indicated by density, thermal, or oxygen stratification.

Biological

The biological sampling sites were selected to answer each specific objective (see "Purpose and Scope" section) of the study. Because these objectives were varied and because samples such as waterfowl are difficult to collect at one location, a total of 40 sites were sampled during 1988-90 (table 2). These sampling sites include three major habitats and generally can be divided into three categories: (1) the Salton Sea (both open-water and near-shore saltwater habitat), (2) agricultural drains and rivers affected by drains (freshwater habitat), and (3) creeks not affected by drains (freshwater habitat).

TABLE 2 near here

Sampling sites for marine algae (fig. 10.) were selected to be uniformly distributed around the Salton Sea to determine if any locations in the sea had significantly higher bioaccumulation of selected drainwater contaminants. Cattails were sampled at five freshwater sites (fig. 10) to determine if bioaccumulation in vegetation was different between drains and natural creeks.

FIGURE 10 near here

Aquatic invertebrates from the south end of Salton Sea were collected at several locations, particularly in the deltas of major drains and rivers (fig. 10). These psuedoestuarine (delta) sites are very significant feeding or foraging areas for many species of birds. Sampling sites for indigenous Asiatic River clams (fig. 10) were selected, subject to availability, in five drains around the Salton Sea, to determine any bioaccumulation differences between drains. One other invertebrate, the crayfish, was collected near the mouths of the New and Alamo Rivers to assess any differences in bioaccumulation between these two rivers.

Figure 10. Biological sampling sites in the study area.

Two species of small forage fish, mosquitofish and sailfin molly, were collected at five sites (fig. 10) to determine differences in bioaccumulation between drains and natural creeks in the Salton Sea area. One composite mudsucker sample was taken at the Alamo River delta to supplement food chain bioaccumulation data for the Salton Sea. Bairdiella, a larger forage fish, were opportunistically sampled at the edge of the Salton Sea near Unit I of the Salton Sea NWR (fig. 10). These fish were sampled because they are important in the food chain and are consumed by piscivorous birds throughout the Salton Sea.

Bullfrogs were sampled only from the Alamo River because of limited availability at other sites. Because their carnivorous food habits put them in a high trophic level, determination of contaminant concentrations in bullfrogs will provide a better understanding of bioaccumulation through one of the freshwater food chains. Spiny softshell turtles were collected at two drain sites (fig. 10) to assess the validity of turtles as indicators of contaminant bioaccumulation. This turtle is high in the food chain and is a resident in many of the drains.

Although sample site selection for birds (fig. 10) was based on the specific objective being addressed, bird availability was a more realistic criterion. Since most birds are highly mobile and can feed in many different locations and habitats, particular sample sites do not necessarily reflect local contaminant conditions. This statement applies to an even greater degree to migratory birds. To overcome these problems, samples of ruddy ducks were collected from the south end of the Salton Sea on their arrival in the autumn, again in the winter and finally in early spring prior to their departure from the sea. In this manner bioaccumulation rates for selected drainwater contaminants can be determined for migratory birds wintering at Salton Sea.

Sampling resident birds (fig. 10), including the Yuma clapper rail, black-necked stilt, and American coot, can provide more information on local drainwater contaminant conditions than can the sampling of migratory wintering birds. This is particularly true for the endangered Yuma clapper rail. (A specimen was salvaged from Wister Wildlife Management Area (WMA).) Because rails have limited home ranges and usually are not migratory, they are likely to reflect local drainwater contaminant concentrations.

Black-necked stilt eggs, juveniles, and adults were sampled extensively throughout the southern part of the Salton Sea and the Imperial Valley. Although most stilts are residents at Salton Sea, during fall and winter some likely are migrants from more northerly areas. This possible migratory pattern makes it difficult to correlate contaminant body burdens in stilts with the area in which they were collected. However, because most of the stilts are resident at Salton Sea, body burdens probably reflect drainwater contaminant conditions in both the sea and adjacent Imperial Valley.

The American coot in the Imperial Valley feeds mostly in freshwater impoundments not usually affected by drainwater; therefore, only one site, Vail 2B drain, was selected for sampling coots. In other areas, such as Kesterson NWR, these resident, mostly herbivorous, birds have served as excellent biomonitors of effects from drainwater contaminants. Coots in the Imperial Valley (Vail 2B drain), because of their association primarily with freshwater, are not expected do show contaminant burdens.

Sampling Methods

Water and Bottom Sediments

Samples for subsurface drainwater were collected from Imperial Irrigation District (IID) sumps throughout the Imperial Valley. The sump pump was manually activated, and the sample was collected in a churn splitter from the outflow pipe to the drainage ditch. Discharge was calculated using the rise in the float stick per unit time and the diameter of the sump (90 in.). For the May 1988 sampling, 106 sumps were sampled throughout the Imperial Valley. Sites were divided into two categories to limit laboratory cost. Sample schedule A included analyses and (or) measurements for specific conductance, temperature, pH, alkalinity, chloride, and selenium. Sample schedule B included the above plus analysis for tritium, hydrogen and oxygen stable isotopes, boron, arsenic, nitrogen (ammonia and nitrite plus nitrate), major ions, iron, manganese, and molybdenum.

Monthly water samples were collected during the 1989 water year from six surface-water sites: New River at international boundary at Calexico, New River at outlet to the Salton Sea, Alamo River at international boundary, Alamo River at outlet to the Salton Sea, Trifolium Drain 1, and the East Highline Canal. The monthly samples included analyses and (or) measurements for specific conductance, temperature, pH, alkalinity, dissolved selenium, dissolved solids, chloride, boron, dissolved nitrogen (ammonia as N and nitrite plus nitrate as N), iron, bromide, and major dissolved ions. Quarterly samples included the above plus dissolved and total trace elements (selenium, arsenic, iron, manganese, molybdenum) and dissolved aluminum. In addition, periodic samples were collected to determine hydrogen and oxygen stable-isotope ratios. Monthly dissolved samples were collected at the centroid of flow. Quarterly samples were collected with either a DH-48 or DH-59 sampler using the equal-discharge-increment method and composited in a churn splitter.

Monthly and quarterly samples also were collected from 15 sumps throughout the Imperial Valley, a subset of the 106 sumps sampled during May 1988. In a manner similar to that of the May 1988 sampling, subsurface drainwater was collected from the sumps by manually activating the float switch and obtaining the water from the outflow pipe to the drainage ditch.

Shallow ground-water samples were collected at three sites in the Imperial Valley, a further subset of the 15 fields sampled monthly. Samples were collected from both shallow lysimeters and from multiple-depth wells for analysis of specific conductance, temperature, pH, alkalinity, dissolved solids, major dissolved ions, dissolved nitrogen (ammonia and nitrite plus nitrate), selenium, boron, arsenic, iron, manganese, molybdenum, strontium, aluminum, lithium, bromide, tritium, and hydrogen and oxygen isotopes. A few select samples were collected for analysis of C-13/C-12 ratio, N-15/N-14 ratio, and S-34/S-32 ratio, along with percent of carbon 14. The lysimeters were sampled by first setting a vacuum and then, several weeks later, applying nitrogen gas to pump out the lysimeter cup for the water sample. The sample was collected from the lysimeter through the teflon tubes. Water at 75 and 199 ft at the northern site, S-417, is artesian and the sample was collected from the flowing well. At the remainder of the wells, water samples were collected using a Bennet pump after evacuating three well-casing volumes.

Water in and near the delta of the Alamo River was sampled three times. Where depth permitted, samples were collected using a modified Van Dorn sampler. Several of the sites in the embayments on the southern end of the Salton Sea were less than 1.0 ft deep, preventing the use of the sampler. At those sites, sample water was collected using a wide-mouthed glass bottle. Bottom-sediment samples were collected using either an Ekman Dredge or a piston corer. All samples were collected from an airboat furnished by Salton Sea NWR personnel. Water samples were collected for analysis of dissolved selenium, arsenic, boron, and isotopes of hydrogen and oxygen. Field measurements were made for specific conductance, temperature, pH, and dissolved oxygen concentration. These measurements were made using a multiparameter unit that was calibrated each day in the field and checked against standards at the end of the day. After the August 1988 sampling trip, subsequent field measurements for dissolved oxygen concentration and percent saturation were made using an oximeter with an internal microprosser and salinity compensation. A salinity-correction factor was applied to earlier oxygen readings in calculating the oxygen saturation.

Biological

Samples of biota were collected from 40 sites (fig. 10) representing subsurface drainwater, ditches, rivers, creeks, impoundments (collectively termed river/drain sites), and the Salton Sea to determine the extent and impact of irrigation drainwater on biota inhabiting the Salton Sea and surrounding habitats (table 2). Samples of biota representing varying trophic levels included vegetation, aquatic invertebrates, fish, amphibians, reptiles, and birds. Table 3 lists the species collected and sample types submitted for contaminant analyses during the 3-year detailed investigation. The occurrence of a particular species at any given site was highly variable because sites presented different habitats. Samples were collected, processed, stored, and later shipped in accordance with instructions provided in U.S. Fish and Wildlife Service (1984,1990).

Table 5 near here

Vegetation was collected from agricultural drainage ditches and from the Salton Sea shorelines with rocky substrate at locations surrounding the Salton Sea. Periphyton was collected and submitted as one composite sample. Algae were collected by hand from rocks or wood piers at the shoreline. Samples of a filamentous green alga (*Enteromorpha* sp.) and a benthic blue-green alga were collected from 14 sites at various shoreline locations around the Salton Sea. Algae, which are primary producers and form the base of most food chains, represent one of the lower trophic levels where initial bioaccumulation of some drainwater contaminants occurs. The species of algae that were collected are incidentally eaten by water birds. Cattail was the only emergent aquatic plant collected as part of the detailed investigation. The roots of this plant are utilized for food by several species of waterfowl. All plant samples were washed of excess mud and debris at the collection site and rewashed prior to being bagged in polyethylene bags and frozen.

Aquatic invertebrate collections included crayfish, waterboatmen, amphipods, pileworms, and Asiatic river clams. Aquatic invertebrates compose most of the diet of shorebirds and several other waterbirds utilizing the Salton Sea. Pileworms were collected by screening sediments through fine-mesh screens, and waterboatmen and amphipods were collected using lighted activity traps. In 1989, waterboatmen, amphipods, and pileworms were composited as one sample, representing a typical shorebird diet. Crayfish were collected from river/drain sites using small seines, composited whole, and put in chemically clean jars. Asiatic river clams were collected from river/drain sites by hand and by screening sediment through a sieve.

In an effort to determine potential bioconcentration of irrigation drainwater contaminants by invertebrates at river and drain sites, clams collected from the Colorado River near Palo Verde, California, were transplanted to the Alamo River, New River, and Trifolium Drain. The collection areas were side channels of the Colorado River, where water quality is similar to that of water entering the All American Canal before it is influenced by irrigation tailwater and subsurface drainwater. Clams were hand-picked from bottom sediment and transported in aerated containers to the Salton Sea NWR. An equal number of clams (n=100) then were put into three plastic-mesh cages approximately 2 ft × 2 ft × 4 ft in size. One cage was placed and securely anchored (at each site) in the Alamo River, New River, and Trifolium drain. Subsamples from each site were collected and analyzed approximately 1 month, 2 months, 4 months, and 15 months after initially being placed at the sites. The clam subsamples were shucked and the soft body tissue was submitted for analyses. All aquatic invertebrate samples were placed in chemically clean jars immediately following collection, frozen, and shipped on dry ice to analytical laboratories.

Four species of fish (mosquitofish, sailfin molly, longjaw mudsucker, and bairdiella) were collected using long-handled dip nets or small seines. Mosquitofish and sailfin mollies were collected in 1988 and 1990 from rivers, creeks, and drains. Longjaw mudsuckers were collected in 1989 from the Salton Sea. Bairdiella were collected in 1989 after they washed onto the Salton Sea shore near Unit 1 of the Salton Sea NWR. For small fish, a minimum of 10 fish or 25 grams of whole fish was composited as a sample and frozen in chemically clean jars. The larger bairdiella were wrapped in aluminum foil and placed in polyethylene bags and then frozen.

Two bullfrogs were collected from the Alamo River, and six softshell turtles were collected from two drains on the Salton Sea NWR. Bullfrogs were speared, and the carcasses were wrapped in aluminum foil and frozen in polyethylene bags. Softshell turtles were trapped in hoop nets baited with commercially prepared tuna. Samples of fat (for organic analyses) and liver tissue (for inorganic analyses) were dissected from the turtles and frozen in chemically clean jars. A sample of turtle eggs also was collected from one female for organic analysis.

Several species of water birds, including ruddy duck, northern shoveler, black-necked stilt, American coot, eared grebe, and white-faced ibis were collected using shotguns and steel shot. These species represent various feeding strategies and higher trophic levels. Livers and breast-muscle tissue of these species were taken from the carcasses and submitted for inorganic and organic analyses. Carcasses of only black-necked stilts also were submitted for inorganic analyses. Eggs from black-necked stilts nesting at Salton Sea also were collected from many locations for contaminant analysis. The contents of each egg were harvested, placed in a chemically clean jar, and frozen. One Yuma clapper rail, a federally endangered species, was salvaged from the nearby Wister Wildlife Management Area (WMA) and submitted for inorganic analyses.

Analytical Methods

Water and Sediment

All water samples for major ions and trace elements were analyzed by the USGS National Water Quality laboratory in Arvada, Colorado, using methods specified by Fishman and Friedman (1985). Concentrations of trace elements in bottom-sediment samples were determined by the USGS Geologic Division's Analytical Facility in Denver, Colorado. Most elements were analyzed by inductively coupled argon-plasma atomic-emission spectrometry following complete mineral digestion with strong acids. Arsenic and selenium were analyzed by hydride-generation atomic absorption, mercury by cold-vapor atomic absorption spectrometry, and boron was analyzed on the hot-water extract.

Water samples for hydrogen and oxygen isotopes, and for tritium concentration, were analyzed by the USGS Isotope Fractionation Project Laboratory in Reston, Virginia. Hydrogen-isotope-ratio analyses were done by the zinc hydrogen-gas generation technique (Kendall and Coplen, 1985). Results are reported in δ as the deviation in parts per thousand (permil) of the isotope ratio in the sample from the isotope ratio in Vienna Standard Mean Ocean Water (VSMOW). Oxygen-isotope-ratio analyses were done by a CO_2-equilibration technique (Eqstein and Mayeda, 1953) that yields activities rather than concentrations. Tritium analyses were done by liquid-scintillation counting of electrolytically concentrated samples.

Monthly water samples collected from the East Highline Canal (Colorado River water) had selenium concentrations of about 2 μg/L and chloride concentrations of 100 mg/L. For selenium, the measured concentrations are close to the detection limit of 1 μg/L. In order to more accurately determine the selenium concentration, as well as the Se/Cl ratio in irrigation water, water samples from the East Highline Canal (downstream of the diversion from the All American Canal) were concentrated in the laboratory by evaporation from large open-top glass chromatography jars. The water was stirred throughout evaporation using a magnetic stirrer. About one month of evaporation at 30-35 °C was required to reduce water volumes nearly 99 percent (about 100-fold concentration).

Evaporations were carried out in two ways: using untreated water and using water acidified to pH approximately 3 by addition of nitric acid before evaporation began. Low pH was maintained in the acid-treated samples to prevent formation of calcium carbonate, which began to appear in the untreated water soon after evaporation started. Large amounts of calcium sulfate were formed during the evaporation of both the acidified and untreated waters. There is evidence of slight selenium incorporation into the solid phases. The evidence is based on analyses of the calcium carbonate itself and on slightly lower Se/Cl ratios in untreated samples in comparison with acidified evaporated samples. Unevaporated and acidified evaporated waters have nearly the same Se/Cl ratios.

Cores were collected in PVC tubes from the Alamo River delta and in the drainage ditch across from sump S-417 by physically pushing the tubes into the sediment. The cores were vertically extruded in 2-cm segments and placed in a N_2-pressurized squeezer that expressed the pore waters through a 0.45-μm sterile filter directly into collection syringes.

Pore waters from the core samples were analyzed for sulfate and chloride according to methods described in Oremland and others, 1990. Sulfide was determined calorimetrically after fixing with zinc acetate according to methods described by Cline, 1969. Nitrate was determined by autoanalyzer (Oremland and others, 1990), iron and arsenic by graphite-furnace atomic absorption spectrometry (Slavin an others, 1983; Schlemmer and Welz, 1986), and selenite by flow-through hydride-generation atomic absorption spectrometry (Oremland and others, 1990). Total-sediment arsenic and selenium were determined on both unseived and less than 60-micron fractions from core intervals according to methods specified by Elrick and Horowitz, 1985. The less than 60-micron fraction (after freeze-drying) also was subjected to a 1M HCl microwave extraction to determine "leachable" arsenic and selenium as described by Brook and Moore, 1988.

Biological

The biotic samples were chemically analyzed at several laboratories under contracts administered through the USFWS Patuxent Analytical Control Facility (PACF), Laurel, Maryland. The specific laboratories, types of analyses performed, year(s) analyses were performed, and sample medium analyzed are summarized in table 4. Several trace elements were analyzed using an inductively coupled plasma scan, and arsenic and selenium were analyzed by atomic absorption spectrometry (AA) using hydride generation; mercury was analyzed using the AA cold-vapor technique. Organochlorine pesticide and Arochlor (PCB) concentrations were determined by solvent extractions and analysis using gas chromatography. The highest acceptable limit of detection for each analyte discussed in this report is given in table 5. Although variations in these analytical techniques (for example, internal standards) existed, basic quality-assurance procedures established by the PACF were used by all laboratories in this investigation. The PACF is responsible for assuring the quality of the chemical analyses it provides through its in-house laboratory as well as monitoring the quality assurance of each contract laboratory. The quality assurance is implemented through a series of quality control and quality-assessment techniques. Quality-control techniques include procedural blanks, duplicate samples, spiked samples, and checks with reference material. Acceptable precision percentages, determined from duplicate samples, and acceptable accuracy percentages, determined from spiked samples, are given in table 6. Quality-assessment procedures include crosscheck analysis in which samples are reanalyzed and round robins in which all laboratories analyze a portion of the same sample and PACF evaluates the results. A crosscheck was applied to this investigation on a subsample of 1989 organochlorine data. The PACF reanalyzed samples that initially had been

TABLE 4 near here

TABLE 5 near here

TABLE 6 near here

analyzed by a contract laboratory. Some differences in values were identified and reanalysis by the contracting laboratory was done. In accordance with current guidelines, the PACF has found all data in this investigation to be of acceptable accuracy and precision.

AREAL DISTRIBUTION OF SELECTED CONSTITUENTS

During May 1986 the California Regional Water Quality Control Board (Regional Board) collected water samples from 119 sumps draining fields in the Imperial Valley to determine the concentration of selected constituents, including selenium, boron, and dissolved solids. In May 1988, the USGS sampled as many of these same 119 sumps as could be located to determine concentrations of an augmented list of constituents from those collected by the Regional Board. To determine the comparability of the two data sets, selenium concentrations from the May 1988 sampling were compared to concentrations from the May 1986 sampling. The two periods were significantly correlated (r^2=0.785, α <0.01) (fig. 11). With a slope of 0.966, the regression model indicates that the majority of selenium concentrations in sumps changed very little over two years. In general, for those sumps having high concentrations of selenium in 1986, concentrations also were high in 1988, and low concentrations remained low. This lack of change in concentration would seem to indicate that the processes controlling selenium concentrations in subsurface drainwater are fairly uniform over long periods of time.

FIGURE 11 near here

Figure 11. Regression plot of 1988 and 1986 selenium concentration in subsurface-drainwater samples collected in the Imperial Valley.

The locations of sites sampled during May 1986 and May 1988 are shown in figure 9. Selenium concentrations for 106 USGS samples ranged from 3 to 300 μg/L, with a median concentration of 24 μg/L. The standard deviation (non-normal distribution) was 58. The areal distribution of the selenium concentrations (USGS samples) shown in figure 12 does not seem to indicate any strongly discernible regional pattern. An area of high selenium concentration (greater than 100 μg/L) is located southeast of the Salton Sea NWR. Land-surface elevations are lowest in the Imperial Valley, aside from those areas inundated by the Salton Sea. Other areas of elevated levels of selenium in subsurface drainwater, however, are spread throughout the Imperial Valley, both along the main topographic axis of the valley and on the periphery.

FIGURE 12 near here

Figure 12. Areal distribution of selenium concentration in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Specific conductance presents a pattern similar to that of selenium. The relation between specific conductance and selenium is $100 \times r^2 = 77.5$, $\alpha < 0.01$. Specific conductance is affected by ionic mobility, which varies with ionic concentration and the chemical composition of the water. The relation between selenium and dissolved solids is $100 \times r^2 = 70.4$ (Regional Water Quality Control Board, written commun., 1986). Both specific conductance and dissolved solids show a distribution similar to that of selenium, with the exception of the area bordering the southern end of the Salton Sea. Specific conductance is referred to for the 1988 data because dissolved-solids concentration was determined on a more limited number of sites. As shown in figure 13, specific conductance at site 4 (IID sump S-38) was 38,200 uS/cm, and selenium concentration was only 15 μg/L. At site 15 (IID sump S-11), specific conductance was 33,800 μS, and selenium was 3 μg/L. Both of these sites had high chloride concentrations: 14,000 and 11,000 mg/L, respectively. It seems that the high dissolved-solids content of the sumps draining these two fields is strongly influenced by the water from the Salton Sea (chloride 14,000 mg/L), more so than by processes occurring within the field. The reducing environment present along the southern boundary of the Salton Sea also could be exerting an influence on the chemistry of these fields; both sites had elevated ammonia concentrations (3.2 and 10 mg/L, respectively), and the reducing conditions could affect the solubility of selenium. This effect will be discussed later in more detail.

FIGURE 13 near here

Figure 13. Areal distribution of dissolved-solids concentration in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

TEMPORAL VARIATION IN CONCENTRATION OF SELECTED CONSTITUENTS

Monthly subsurface drainwater samples were collected during the period August 1988 to August 1989 from 15 fields (previously identified) to determine the temporal variation in constituent concentrations. Additionally, results from the May 1988 samples were compared with the monthly monitoring data to evaluate whether the May samples are representative for the period. Temporal variations in selenium concentration during the sampling period are shown for all 15 fields in figure 14.

FIGURE 14 near here

Comparison of May 1988 selenium concentrations at each of the 15 sites with the mean concentrations of the monthly samples indicates that May samples at most of the sites are reasonably representative of the general water quality at each site. The selenium data for the 15 sites, including standard deviation and also selenium load in pounds per year, are summarized in table 7. The load values are rough estimates calculated by adding the monthly selenium concentrations times discharges; nevertheless, these load estimates provide an indication of the amount of selenium contributed by each field. The data also show that the volume of flow from the sump is the major variable influencing selenium loading. Whereas the range of selenium concentration in samples of subsurface drainwater was one order of magnitude, the range in volume of subsurface drainflow was three orders of magnitude. Overall, the highest loads occurred only during high discharges.

TABLE 7 near here

Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley, August 1988-August 1989.

Although most of the May selenium concentrations seem to be representative of the average concentration, several sites had large variances between the May 1988 sample and the monthly mean. At 11 of the 15 sites, the May selenium concentration fell within one standard deviation of the monthly mean. At the four other sites, S-423, S-417, S-4, and S-352, the May selenium concentration fell just outside one standard deviation of the mean. None, however, was sufficiently outside the range as to change the ranking of the site from one with low concentration to one with high concentration or vice versa. Se/Cl ratios that were calculated from the monthly samples also indicate that May samples are representative of irrigation drainage at the 15 sites. Table 7 gives the average Se/Cl ratio for the monthly samples as well as the values for the May 1988 sample. The Se/Cl ratios for the May 1988 samples from sites S-154 and S-142 (0.003 and 0.073) vary the most from the average of the monthly values. The very low Se/Cl ratio at S-154 might indicate the presence of reducing conditions that are removing selenium from the water. No discharge into sump S-142 was observed at any time during the year-long sampling period. Because no flow was observed, this site is not typical of actively irrigated fields in the Imperial Valley.

The relation between selenium and chloride concentrations was demonstrated and discussed previously in this report. Similar evaluation of monthly samples from the 15 fields is summarized in table 7. Regression analysis of selenium against chloride was done to determine if conclusions drawn from the May 1988 valleywide sampling hold true for the monthly sampling. The average of the monthly regressions is 64 percent, indicating that selenium concentration varies directly with chloride concentration. Data from the monthly regressions show that for 7 of the 15 sites, the $100 \times r^2$ value is greater than 80. Coupled with the previous discussion of the May 1988 sampling, these data demonstrate that the relation between selenium and chloride is not affected by seasonal variations. Four of the 15 sites have $100 \times r^2$ values between 50 and 80, also indicating that similar processes control both selenium and chloride. The remaining sites do not demonstrate any correlation between these two constituents. Site S-142 has a $100 \times r^2$ value of only 1.9, $\alpha = 0.63$. However, as mentioned above, no discharge into this sump was observed. Selenium concentrations at S-142 ranged from 11 to 17 µg/L, but in no apparent pattern. Hydrogen-isotope ratios for November 13, 1988, and March 15, 1989, indicate that evaporation was occurring (δD increased from -99 to -82 permil). Although a concurrent increase in dissolved-solids concentration was detected, the pattern does not parallel that of δD. Also, there is no pattern of increasing selenium concentration during this period. Concentrations of major ions indicate that water entering the sump during the period between the March 15 and April 10, 1989, samplings was lower in dissolved-solids concentration. Possibly, this water was from precipitation and (or) surface runoff from a rain.

Regression of selenium against chloride at site S-265 had a 100 × r^2 of less than 1, indicating no correlation between these two constituents. Selenium concentrations at this site were moderately high, ranging from 50 to 99 μg/L for the monthly samples. The average Se/Cl ratio at this site of 0.036 is greater than the average ratio for the 15 sites, 0.025, and greater than the ratio for the May 1988 sampling, 0.02. The August 1989 sample had one of the highest observed ratios, 0.06, possibly indicating a selenium source. This site also had the highest subsurface-drainwater discharges, along with the highest selenium load, of the 15 sites.

Water from site S-269 also had a poor correlation between selenium and chloride, as demonstrated by a 100 × r^2 value of 3 (table 7). Selenium concentrations at this site were high, ranging from 180 to 360 μg/L. Again, this site is atypical of fields in the Imperial Valley in that concentrations of selenium do not parallel those of chloride and that several Se/Cl ratios were high, 0.45 and 0.56 for samples in November and April 1988 and 1989, respectively. Subsurface drain flow at this site, 1.16 ft^3/s, was among the highest observed in the August 1989 sampling. Although the remaining flows were average in comparison with the other sites, ranging from 0 to 0.079 ft^3/s, this (August 1989) high flow coupled with the high selenium concentration, 240 μg/L, produced the second highest selenium loading of the 15 sites, 54.6 lb/yr.

At site S-226, the selenium to chloride regression for subsurface drainwater samples yielded a $100 \times r^2$ value of 28. α =0.05. Chloride concentrations at this site are notable in that the highest subsurface drainwater concentration of the study, 19,000 mg/L, was detected in the August 23, 1988, sample. The corresponding selenium concentration was 280 μg/L. This site, along with S-226, had the highest selenium concentrations of the study.

Although the above sites seem to indicate a selenium source, subsurface drainwater from site S-154 had the lowest Se/Cl ratio of the 15 sites, 0.0033. All the monthly ratios at this site were an order-of-magnitude less than the overall average for the 15 sites. Selenium concentrations at this site were in the lower range, 2-29 μg/L. The selenium load at this site also was the lowest of the 15 sites, 0.4 lb/yr--even though evaporative concentration of applied water is occurring, as evidenced by an average chloride concentration of 6,400 mg/L and a $\delta^{18}O$ of -10.9 permil, in comparison with 90 mg/L and -13 permil, respectively, for water in the East Highline Canal. The field drained by this sump is in an old lakebed (Mesquite Lake), and the field reportedly is difficult to farm; as a result, irrigation has been applied repeatedly to leach the accumulated salts from the soils (B.S. Baharie, USGS, oral commun., 1989). In comparison, water from lysimeters located adjacent to the sump had dissolved-solids and selenium concentrations that were significantly higher than those detected in subsurface drainwater collected from the sump. For example, the dissolved-solids concentration for water in the lysimeter at 5 ft was 49,000 mg/L, with a selenium concentration of 120 μg/L, δD and $\delta^{18}O$ of -75.5 and -7.85 permil, and nitrate-as-N concentration of 110 mg/L. Insufficient water was collected for tritium analysis. Water from the lysimeter at 10 ft had a tritium concentration of less than 0.1 TU, indicating water of pre-1952 origin. The water from the sump draining the field had an average tritium concentration for three samples of 36 TU's, a little higher than applied irrigation water, along with concentrations of selenium, dissolved solids, and nitrate of 19 μg/L, 12,700 mg/L, and 5.8 mg/L, respectively. Although Se/Cl ratios generally were not calculated for ground-water samples, the Se/Cl ratio for water in the lysimeter at 5 ft was 0.0043. This ratio is within the range for subsurface drainwater at this site (Se/Cl ratio of 0.003 ± 0.001), even though dissolved-solids concentrations differ greatly. Because the area occupies a lakebed, conditions similar to those found in the Salton Sea might have existed in the past. Under these conditions, selenium could be removed from the water by bacteria and be deposited in the elemental form (Oremland, 1989). If this selenium either entered the biota or remained in the elemental form, it effectively was removed from the system. Mineral salts also could have been deposited during evaporation of this lake. Leaching of these salts, as the field was brought under irrigation, likely accounts for the high chloride content detected during sampling, both within the field and on its periphery.

Figure 14 shows monthly selenium and subsurface drain flow for the 15 sites. These graphs illustrate how selenium concentration is influenced by subsurface drain flow. When drain flow increases, selenium decreases, and as drain flow decreases, selenium increases. Usually, any such increases or decreases in drainflow are reflected by a concurrent but opposite change in selenium concentration. For some months, such as March through August, the response of concentration to discharge (site S-423, for example) appears to be lagging. Timing of reactions and (or) adsorption may be reasons for this lag.

Monthly water samples at selected surface-water sites were collected during October 1987 to August 1988 to determine the time-series variation in constituent concentrations. Coupled with water discharge, this information can be useful in providing an estimate of constituent loading to the Salton Sea. The median selenium concentration in the Alamo River at the outlet to the Salton Sea was 8 μg/L (table 8). This concentration at a flow 600,500 acre-ft for the 1989 water year gives a load of 6.5 tons of selenium. The New River at its outlet to the Salton Sea delivered 2.5 tons of selenium in the 1989 water year, 2.0 tons of which was contributed by irrigated agriculture in the Imperial Valley. Salt loading to the sea also is substantial. The combined load of the New and Alamo Rivers is 3.6 million tons of salt for the 1989 water year. This load, coupled with an evaporation rate of 5.6 ft/yr in the Salton Sea (Hely and others, 1966), results in increasing salinity levels in the Salton Sea.

TABLE 8 near here

IGURE 15
ear here

Selenium concentration in the Alamo River at the outlet to the sea is fairly constant. The standard deviation of 2.1 μg/L includes results from an April sample in which total selenium concentration was 2 μg/L (a probable outlier). A concurrent sample for dissolved selenium had a concentration of 8 μg/L. Flow in the Alamo River, effectively, is an average of the irrigation drainage from the Imperial Valley and varies seasonally with irrigation and with infrequent tropical storms (fig. 15). Water quality in the New River at its outlet to the sea is strongly influenced by the quality of water crossing the international boundary at Calexico, where median selenium concentration was 2 μg/L. Water crossing the international boundary constitutes about 40 percent of the total flow in the New River at its outlet to the Salton Sea. Consequently, selenium concentrations in the outflowing water from the New River are lower than in water from the Alamo River (about 50 percent). Colorado River water used for irrigated agriculture in the Imperial Valley has a median selenium concentration (for monthly samples collected during the 1989 water year) of 2 μg/L, with a standard deviation of 0.3.

Figure 15. Mean daily discharge in the Alamo River near Niland and the New River near Westmorland, water year 1989.

Elemental ratios in monthly water samples collected from the major rivers also were examined to determine the presence of sources or sinks of selected constituents within the agricultural system of the Imperial Valley. During the analysis of subsurface drainwater, Se/Cl ratios were evaluated to determine sources and (or) sinks of selenium. These ratios also can be used in the rivers to determine losses or gains of selenium. Water in the East Highline Canal had a median Se/Cl (× 1,000) ratio of 0.022 (table 8). Representing the cumulative mixing of subsurface drainwater, the Alamo River is the best available indicator of the effects of irrigated agriculture on water quality in the Imperial Valley. The median Se/Cl ratio in the Alamo River at the outlet to the Salton Sea was 0.017. These two ratios, 0.022 ±0.0035 and 0.17 ±0.0026, are statistically different (Kruskal-Wall Test Statistic = 14.026; chi-square distribution value is 3.84, $\alpha = 0.05$). The ratios indicate a small loss (about 20 percent) of selenium in comparison with chloride. In general selenium in most of the Imperial Valley, as indicated by the Se/Cl ratio of input versus output water, behaves fairly conservatively even as it is transported to the Salton Sea. Even a generalized comparison shows that both selenium and dissolved solids increase by a factor of about four from the East Highline Canal to the Alamo River at the outlet to the Salton Sea (2 to 8 μg/L and 686 to 2,670 mg/L, respectively). The New River does not present a valid case for examination because 40 percent of the flow at the outlet to the Salton Sea originates in Mexico and is composed mainly of domestic and municipal effluent. For Trifolium drain 1, the Se/Cl ratio is 0.012. This ratio indicates that some loss or sink of selenium is occurring relative to chloride. Trifolium drain 1 is located in the irrigated northwestern part of the Imperial Valley, west of the New River. Some fields in this area are affected by reducing conditions or by high chloride low Se from the Salton Sea. Mixing of water from these fields with water unaffected by reducing conditions might account for the lower Se/Cl ratio in Trifolium drain 1. Water in this drain discharges directly to the Salton Sea about 2 mi southwest of the New River delta.

A comparison of Se/Cl ratios of input and output water indicate that little selenium is lost in the agricultural system of the Imperial Valley. Apparently, however, a considerable dilution of subsurface drainwater occurs between discharge from the sumps to the ditches and the outlet to the Salton Sea. As previously mentioned, the selenium load discharged to the Salton Sea by the Alamo River is 6.5 tons/yr. Assuming that the May 1988 subsurface drainwater sampling of 106 sumps throughout the Imperial Valley is representative, the discharge-weighted selenium concentration is 25 $\mu g/L$, which is the same as the median selenium concentration. The median Se/Cl ratio for the sites is 0.02, indicating that little to no gain or loss in selenium has occurred, taking in to account a standard deviation of 0.015. In order to reach a final selenium concentration of 8 $\mu g/L$ in the Alamo River at the outlet to the Salton Sea, considerable dilution must occur. The mixing is computed by the following equation:

$$(302{,}748\ ft^3/s)(0.0027)(0.002)X + (302{,}747)(0.0027)(0.025)(1\text{-}X) = 6.5\ \text{tons},$$

where $X = 0.74$, $1\text{-}X = 0.26$.

The equation indicates that of the total discharge, 302,748 ft^3/s, in the Alamo River at the outlet to the sea, 74 percent or 224,000 ft^3/s must come from a source with very low selenium concentration. The equation assumes a selenium concentration of 2 $\mu g/L$ in the dilution water. This water likely comes from either tailwater runoff, seepage from unlined canals, or other input of water with very low selenium concentration. This relation considers that there is no selenium sink in the ditches or river. Examining chloride and dissolved solids in the same manner indicates that the actual dilution is about 65 percent or 196,786 ft^3/s of the total discharge in the Alamo River at the outlet to the Salton Sea. Assuming that chloride is being processed conservatively in the agricultural system, a 15 percent loss of selenium in the ditches or river is needed to account for the difference in dilution. The

Se/Cl ratios in subsurface drainwater and in the Alamo River at the outlet to the sea also indicate a 15 percent loss of selenium, although the standard deviations are high enough to question the accuracy of this value. Because of the lower selenium concentration in the New River and the high proportion of flow from Mexico, a similar calculation was not made for the New River.

Boron can be examined in a manner similar to the examination of selenium discussed above. Boron concentration in the Alamo River at the outlet to the Salton Sea was 560 μg/L; using this value, one can calculate a boron load to the Salton Sea during the 1989 water year of 457 tons. Substituting the boron values into the dilution equation (Colorado River water = 135 μg/L and subsurface drainwater = 1,800 μg/L) yields a dilution factor of 74 percent, the same as that for selenium. This dilution factor--along with the B/Cl ratios, which are 0.78 for subsurface drainwater and 1.12 for the Alamo River site--also indicates that some boron gain occurs in the ditches or river. Unlike selenium, which is removed from the water of the Salton Sea, boron concentrates with evaporation to a concentration of 11,000 μg/L. Boron to chloride ratios indicate that in the movement of water through the agricultural system, some boron is lost. The B/Cl ratio, in order of movement, decreases from 1.54 in Colorado River water to 0.78 in subsurface drainwater; increases to 1.12 in the Alamo River; and finally decreases to 0.78 in the Salton Sea.

PROCESSES CONTROLLING THE CONCENTRATION OF SELENIUM AND OTHER CONSTITUENTS

Subsurface Drainwater

Physical Characteristics of Fields

There are many variables affecting concentrations of selenium and other constituents in subsurface drainwater. The physical characteristics, especially soil characteristics, of individual fields are one of the factors that control these concentrations in drainwater. The physical layout of the field (including the spacing of subsurface drains), piezometric surfaces, and transit time of water in the field all are variables controlled by the soil characteristics.

The irrigation cycle in the Imperial Valley begins as water is requested by the farmers and delivered to the field by a 1,675-mile network of canals operated by IID. Most fields use furrow (flood) irrigation in which water applied to the head of the field flows downslope to the tail and the location of the drainage ditch and sump. Most fields in the Imperial Valley have gentle slopes of less than 0.2 percent. For clayey soils, such as those in the Imperial Formation, irrigation runs as much as 0.5 mi in length are effective. For more sandy soils, such as the Rositas, shorter irrigation runs of 300 ft or less are desirable (Zimmerman, 1981, p. 39). Soil characteristics define both the rate and path of water movement in the fields, and thus determine the spacing of subsurface drains (Hwand and others, 1974, p. 273). The transit time of the water within a field and the water levels before, during, and after irrigation will vary according to soil type. In clayey areas, water applied to the surface flows through cracks in the soil and through trenches dug during installation of subsurface drains. Excavation during installation of subsurface drains and backfill with topsoil results in an increased permeability of the trenches. Because of this increased permeability, most of the applied water flows through the trenches directly to the drains. Recent studies by Tod and Grismer (1988) at the University of California Field Station near Meloland indicate that subsurface drain flow in clayey soils returns to base-flow conditions within 30 hours after irrigation

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(fig. 16). The short duration of increased discharge occurs because of rapid trench flow. Even though discharge returns to base-flow conditions within about one day, drainage efficiencies of only 25 percent result (both ground-water and trench flow are subtracted from drainflow in computing drainage efficiency prior to division by the amount of deep percolation) (Tod and Grismer, 1988, p. 7).

Figure 16. Contribution of trench flow to subsurface drainflow from a typical sump in the Imperial Valley.

Irrigation applied to the field is accounted for in the following manner. Tailwater is runoff that flows directly from the surface of the field to the drainage ditch. This flow occurs when either too much water is applied or earthen dikes retaining water at the tail of a field break. This flow is significant to the dilution of subsurface drainwater and will be discussed later. Water also is lost by evapotranspiration. According to Zimmerman (1981), "Evapotranspiration from growing crops can easily exceed 6 ft of water per year in this area. In the hot months in summer it may exceed 1/3 in. of water per day." Of the water percolating through the soil, subsurface drains (at a depth of about 6 ft) affect only water that is within about 3 m (horizontal distance) of the drain (Tod and Grismer, 1988, p. 7). Water at greater distances is unaffected and moves as recharge to the aquifer beneath the field (fig. 17). Measurements of tritium concentration indicate that water near (within 3 m) the drains is in a null zone, neither moving rapidly toward the drain, nor toward the aquifer as quickly as water farther away (Tod and Grismer, 1988). The median tritium concentration in pore water from 14 soil samples collected at a depth of 3 ft near drains was 30.1 TU's, about the composite age of recently applied Colorado River water. Tritium concentrations of samples from a depth of 6 ft near the drains have a median concentration of 48 TU's, indicating water with a transit time of about 6 years. These two data sets are significantly different in their distribution (Student's T of -4.0189; significance level, 4.45E-4, $\alpha = 0.05$).

FIGURE 17 near here

Figure 17. Movement of water and layout of subsurface drains and soil-sampling sites in a typical field in the Imperial Valley.

For the 15 fields sampled during 1989, the soil type ranged from Imperial Formation clays in the northern part of Imperial Valley to the Rositas sands on the East and West Mesas. The Imperial Formation soils are nearly level, moderately well drained silty clay in the lacustrine basin. These soils require good management practices and tile drains to maintain favorable salt balance and to keep the water table below the root zone (Zimmerman, 1981, p. 5). The Rositas are "nearly level to moderately steep, somewhat excessively drained sand, fine sand, and silt loam in alluvial basins and on fans and sandhills" (Zimmerman, 1981, p. 7). The spacing of subsurface drains is based on the soil type, and ranged from 50 feet in the northern part of Imperial Valley where silty clay soils are present to 400 feet in East and West Mesas where sandy soils are present (Imperial Irrigation District, written commun., undated)).

Evaporative Concentration

Concentrations of hydrogen and oxygen isotopes and tritium were determined in water samples collected from sumps throughout the Imperial Valley to determine the source of water and processes that have affected subsurface drainwater. Hydrogen and oxygen isotopes, which are conservative in their chemistry, provide the ability to distinguish between an increase in dissolved-solids concentration due to leaching without evaporation and an increase in dissolved solids due to evaporation (Fontes, 1980, p. 122). Other indicators such as elemental ratios also can be used, but their interpretation may be complicated by solubility-product considerations in concentrated waters. Evaporation in an arid environment such as the Imperial Valley causes fractionation, which results in enrichment of the heavier isotope in the water that remains. For hydrogen and oxygen, this means that deuterium and oxygen-18 are enriched relation to H and ^{16}O. The isotope concentrations are reported as δD and $\delta^{18}O$ in permil, where

$$\delta D = \frac{D/H\ \text{sample}}{D/H\ \text{standard}-1} \times 1{,}000 \qquad (1)$$

and

$$\delta^{18}O = \frac{\frac{18O}{16O\ \text{sample}}}{\frac{18O}{16O\ \text{standard}-1}} \times 1{,}000. \qquad (2)$$

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The standard for comparison is Standard Mean Ocean Water (SMOW).

For drainwater in the Imperial Valley it was found that $\delta D = 5.4(^{18}O/^{16}O)-34.2$. The standard error of the slope is 0.156. In a study of irrigation drainage wells in the Juarez Valley of Mexico, Fontes (1980, p. 122) found that $\delta D = 5.8(^{18}O/^{16}O)-21$. A slope of 5.8 for the regression model is indicative of evaporative concentration and the increase in salinity (dissolved solids) is due to evaporation (Fontes, 1980, p. 122; Craig, 1966, p. 1544). The regression lines of the plots from the two studies have similar slopes, 5.8 and 5.4, indicating that evaporative concentration is producing the range in dissolved-solids concentration observed for subsurface drainwater in the Imperial Valley. The regression of hydrogen and oxygen isotopes along with the meteoric water line is shown in figure 18. Of particular significance is that the $100 \times r^2$ value for the regression is 96, $\alpha < 0.01$, indicating that subsurface drainwater in sumps throughout the Imperial Valley have a single source of water. Colorado River water used for irrigation in the Imperial Valley has a δD of about -103 and a $\delta^{18}O$ of about -13. These concentrations plot on the lower end of the regression line shown in figure 16, indicating that the Colorado River is the source of subsurface drainwater. The isotopic relation between hydrogen and oxygen as discussed can be extrapolated to include Salton Sea water. This extrapolation shows that water in the Salton Sea, which is the terminus of subsurface drainwater in the Imperial Valley, also is the product of evaporative concentration of Colorado River water (Craig, 1966, p. 1544).

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Figure 18. Regression plot of hydrogen and oxygen isotopes and the meteoric water line for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Although the regression of hydrogen and oxygen isotopes described above has a 100 × r^2 value of 96, there are several points that clearly do not follow the trend indicated by the model. Coplen (1976) found that "Local present day precipitation in the Salton Sea area has an average isotopic composition of: δD equals -60 permil and $\delta^{18}O$ equals -7.2 permil." Water from San Felipe Creek, which flows from the Santa Rosa Mountains to the Salton Sea on its southwestern side, had δD and $\delta^{18}O$ values of -58 and -6 permil, respectively. These points plot to the left of the regression line and are indicative of water from local precipitation. The sump (SS-26) at site 12 (fig. 9) drains a field adjacent to the Salton Sea between San Felipe Creek and San Felipe Wash (fig. 9). Water from this site plots to the left of the regression line at δD=-90 permil and $\delta^{18}O$=-9.45 permil, indicating a mixture of evaporated Colorado River water and water from local precipitation. Water from two springs northeast of the Salton Sea near the Coachella Canal also plots to the left of the regression line and likely represents ground-water flow from the Chocolate Mountains that is derived from local precipitation (Craig, 1966).

Selenium

The isotope data indicate that evaporative concentration of irrigation water produces the range in dissolved-solids concentration observed in subsurface drainwater. The hypothesis for this study was that selenium detected in this drainwater also results from evaporative concentration of Colorado River water. For comparison, in other areas such as the San Joaquin Valley it has been found that high levels of selenium result from oxidation of reduced Se minerals in the Coast Ranges or in soils derived from the Coast Ranges and from evaporative concentration (Deverel and Fujii, 1987).

Several methods of determining the cause of high selenium concentrations in subsurface drainwater are examined. The first is the relation between hydrogen isotopes and selenium concentration. Regression of δD against selenium concentration had a $100 \times r^2$ value of 2.5, $\alpha = 0.33$. The regression plot shows that data from six sites strongly affect the δD-to-selenium relation. These six sites (4,9,12,14,15, and 16) represent sumps draining fields in a narrow band along the southern end of the Salton Sea. Water in these fields is affected by high chloride concentrations from the Salton Sea and (or) reducing conditions present in the area. These sites are atypical of the main growing area of the Imperial Valley and as such can be deleted from the regression relation. Several of these sites--such as site 12,which was discussed previously--also are influenced by local precipitation. Eliminating these points from the regression yields a $100 \times r^2$ value of 62, indicating a significant relation between δD and selenium. The δD and $\delta^{18}O$ regression demonstrated that δD in drainwater is an indicator of evaporative concentration of Colorado River water. The δD against selenium regression, therefore, shows that selenium in subsurface drainwater also results from evaporative concentration of Colorado River water.

Elemental relations between selenium and several conservative constituents also show that selenium in subsurface drainwater is derived from Colorado River water. As previously mentioned, the δD value in drainwater from the Imperial Valley is an indicator of evaporative concentration. Regression of δD with chloride, which is a routinely measured constituent that is conservative in both its chemistry and its transport, can be used as a link to selenium. Regression of deuterium aginst any conservative constituent should have a high r^2. In subsurface drainwater, chloride concentrates to levels approaching those measured in the Salton Sea. The regression of δD against chloride concentration (fig. 19) has an initial $100 \times r^2$ of 61, α <0.01, indicating that chloride in drainwater is derived from evaporative concentration of irrigation water. The regression model clearly is effected by concentrations at three sites that plot to the lower left of the regression line. These sites (9, 12, and 16) are along the southern end of the Salton Sea. Because subsurface drainwater from these sites is affected by local precipitation or runoff from outside the study area, these sites are atypical of the main growing area in the Imperial Valley. Elimination of these points from the regression gives a recomputed $100 \times r^2$ of 83, indicating an excellent correlation between evaporative concentration (δD) and chloride.

FIGURE 19 near here

The next step is to evaluate the correlation between chloride and selenium. This data set (103 samples) is much larger than the previous one (39 samples). Regression of selenium against chloride yields a 100 × r^2 of 33, apparently not a significant relation (fig. 20). However, the regression model is strongly affected by the three points at the upper end of chloride concentration and to the right of the regression line. These sites (4, 14, and 15) are in fields along the southern end of the Salton Sea that are strongly influenced by high chloride concentration (14,000 mg/L) in the Salton Sea. Eliminating these three data points, as well as those from the earlier δD and Cl regression as atypical of the Imperial Valley gives a 100 × r^2 of about 71 (fig. 20), demonstrating that selenium concentrations in subsurface drainwater are controlled by evaporation of Colorado River water in a manner similar to that of chloride.

FIGURE 20 near here

Figure 19. Regression plot of hydrogen isotopes and chloride for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 20. Regression plot of chloride and selenium for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Although most analyses were for total selenium (all oxidation states), limited sampling to determine selenite-to-selenate ratio was performed in June 1989 by personnel from the USGS National Research Program Office in Menlo Park, California. Water collected from site 8, sump S-417, had a total selenium concentration of 275 μg/L--271 μg/L of which was in the selenate form and only 4.24 μg/L was in the selenite form. This analysis verified that most of the selenium in subsurface drainwater is in the form of the highly soluble selenate, and only a small portion is the sparingly soluble selenite. In comparison, water in the drainage ditch to which sump S-417 discharges had a total selenium concentration of 3.31 μg/L. Of this total, 1.41 μg/L was in the form of selenite and 1.91 μg/L in the form of selenate, indicating that some reduction may be taking place in the drainage ditches.

Elemental ratios provide a means to evaluate water-quality changes that occur in irrigation water as it moves through the agricultural system. Selenium, as the element of focus for this study, can be compared to a variety of cations and anions to demonstrate compositional changes in water quality or to show sources or sinks of selenium. Chloride is chosen for comparison because it is conservative in its chemistry, and it is highly soluble. Colorado River water, as sampled from the East Highline Canal, had a selenium concentration of about 2 μg/L and a chloride concentration of about 100 mg/L. These concentrations give a Se/Cl ratio $\times$ 1,000 of 0.02 for irrigation water in the Imperial Valley. This ratio should remain constant as water moves through the agricultural system if there are no sources or sinks that affect the elements differently. Changes in the ratio occur if solubility affects one or the other ion, oxidation-reduction reactions take place, and (or) biological reactions selectively utilize one element or the other. An increase in the ratio indicates a Se source (such as Se in soil) or Cl sink, and a decrease in the ratio indicates a Se sink (sorption or biological reduction) or a Cl source (dissolution of evaporated salt). Se and Cl can cycle through the agricultural system with each behaving exactly the same--precipitating and dissolving alike and with no redox processes. In this study, evaporation (as confirmed by its relation to δD) is the only physical process shown to be affecting both elements similarly. Analytical error for low ranges of selenium concentration can produce a substantial change in Se/Cl ratio. The highest selenium concentration of the study, 340 μg/L, was detected at Sump S-417, which is just south of the Salton Sea. The chloride concentration at this site was 15,000 mg/L, about the same as in the Salton Sea. These concentrations give a Se/Cl ratio of 0.023, close to that in the East Highline Canal. The similarity of the ratios indicates that selenium at elevated levels can be accounted for by evaporative concentration of irrigation water.

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The median Se/Cl ratio for 119 sites (sumps) in the Imperial Valley sampled during May 1988 is 0.02 (fig. 21). Water in the Alamo River at the outlet to the Salton Sea is representative of most of the irrigation drainage from the Imperial Valley, containing both subsurface drainwater and tailwater runoff. With a selenium concentration of 9 μg/L and a chloride concentration of 530 mg/L, the Alamo River site had a Se/Cl ratio of 0.17. This compares favorably with both the median ratio for subsurface drainwater and the ratio in the East Highline Canal. The standard deviation for the 119 sites is 0.015. The minimum ratio is 0.00027 and the maximum is 0.073, with 50 percent of the ratios falling between 0.01 and 0.03.

Figure 21. Selenium to chloride ratios in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Examination of the Se/Cl ratios in specific areas of the Imperial Valley provides insight into the processes that affect the distribution of selenium in subsurface drainwater. For example, sites 3, 4, 5, 12, and 15 are sumps SS-4, SS-38, SS-45, SS-26, and SS-11, which drain fields near the southern end of the Salton Sea. As previously discussed, subsurface drainwater at these sites is influenced by high chloride concentrations from the Salton Sea and also by reducing conditions present in the soils. The Se/Cl ratios were 0.0012, 0.0011, 0.0015, 0.0016, and 0.0003, respectively. These very low ratios indicate a selenium sink. Explanation of this removal can only be hypothesized or inferred from other constituent concentrations. Each of these sites is along the southern edge of the Salton Sea. Because subsurface drains in the fields generally are located 6 ft below land surface, which is at or below the current elevation of the Salton Sea, the resulting piezometric-surface differential could produce the high chloride concentrations detected in the drainwater. It is likely that reducing conditions also are present at site 15, as indicated by an ammonia concentration of 10 mg/L as N and an iron concentration of 1,500 μg/L. Even though subsurface drainwater at these sites is highly evaporated (δD equaled -68 and $\delta^{18}O$ equaled -6.75 permil), selenium concentrations were fairly low (3, 15, 6, 5, and 15 μg/L, respectively). These sites were eliminated from the earlier regressions showing the correlation between selenium and evaporative concentration. Because selenium in the inflowing water to the Salton Sea is biologically removed, water flowing from the sea to the subsurface drains is depleted in selenium and enriched in Cl, D, and ^{18}O. This removal of selenium from the water accounts for the very low Se/Cl ratios observed at these sites. The low Se concentrations may be attributed to redox reactions in reducing soils or to mixing with Salton Sea water.

The Salton Sea also is a prime example of a selenium sink. The selenium concentration in the sea is 1 $\mu g/L$, and chloride concentration is 14,000 mg/L. These concentrations give a Se/Cl ratio of 0.00007. Bacteria in the sea may be removing selenate from the inflowing water and concentrating it as elemental selenium in the deltaic sediments of the New and Alamo Rivers. This selenium- removal process in the Salton Sea, which will be discussed later, also can affect subsurface drainwater in the fields.

Sites having low to very low Se/Cl ratios are easily explained, but three sites, 33, 36, and 101, had significantly higher Se/Cl ratios of 0.073, 0.066, and 0.046, respectively, indicating possible sources of selenium. At site 33 (sump S-142), 13 monthly samples collected during the study had an average Se/Cl ratio of 0.046. During the monthly sampling at this site, however, no measurable discharge into the sump was observed. Observations made during sampling indicate that the field was irrigated in November 1988 and again in July 1989. Concentrations of hydrogen and oxygen isotopes show that water in the sump experienced some evaporative concentration. The δD and $\delta^{18}O$ was -97.0 and -11.7 permil in October 1988. Coincident with the observation of water on the field in November was a slight decrease in δD and $\delta^{18}O$ to -99.0 and -11.9 permil. Between November 1988 and March 1989, isotope concentrations increased to -82.0 and -8.9 permil. One hypothesis is that because the sump had been unused for a long time, it may have contained rainwater that had not flushed out. Rainwater would be depleted in Cl relative to D; also, the Se could desorb from the sump walls and bottom soils.

At the other two sites that had high Se/Cl ratios, 36 (S-214) and 101 (S-202), no detailed analyses were performed. These sites had chloride concentrations of 610 and 260 mg/L, respectively. Although discharge at sites 36 and 101 was measured during later sample collection, no additional samples were collected during the study.

If selenium concentrations at these three (high Se/Cl ratio) sites do indicate a source of selenium, that source is not very significant, in comparison with evaporative concentration, for the valley as a whole. Even though these Se/Cl ratios are the highest measured, the selenium concentrations of 40, 16, and 12 μg/L are not especially high.

Boron

Boron in subsurface drainage behaves in a manner similar to that of selenium in those areas where selenium remains in its +VI oxidation state. In the previous discussion of selenium in subsurface drainwater, it was shown that the correlation between δD and concentrations of Se and Cl indicated that evaporative concentration of Colorado River water was the primary process

FIGURE 22 near here

controlling soluble-salt concentration. Regression of D/H and chloride showed that chloride concentration also is controlled by evaporation (fig. 22). In evaluating the relation between D/H and chloride, the fields adjacent to the southern end of the Salton Sea were considered atypical of the Imperial Valley. Because of high concentrations of chloride from the Salton Sea and inflow from drainages outside the study area, sites 4, 9, 12, 14, 15, and 16 (fields drained by sumps S-38, S-332, SS-26, S-337, SS-11, and S-43, respectively) were deleted. Regression of boron against chloride for log-transformed data at the remaining sites demonstrates that evaporative concentration of Colorado River water is the principal process controlling boron concentrations in subsurface drainwater in the Imperial Valley ($100 \times r^2$

FIGURE 23 near here

$= 65$, $\alpha<0.01$, h=32) (fig. 23). In 1986 the Regional Water Quality Control Board collected samples from 119 sites throughout the Imperial Valley. Analysis of this larger data set by regression of boron and dissolved solids confirms the strong correlation between boron and evaporative concentration

FIGURE 24 near here

($100 \times r^2$ of 77, $\alpha<0.01$) for log-transformed data(fig. 24).

Figure 22. Regression plot of hydrogen isotopes and $\log_{10}$ normalized chloride for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 23. Regression plot of $\log_{10}$ normalized chloride and boron for subsurface-drainwater samples collected during in the Imperial Valley, May 1988.

Figure 24. Regression plot of $\log_{10}$ normalized boron and dissolved solids for subsurface-drainwater samples collected in the Imperial Valley, May 1986.

Elemental ratios of boron to chloride (B/Cl) in subsurface drainwater were examined to determine similarities with, and differences from, Se/Cl ratios. The median B/Cl ratio × 1,000 for the 40 subsurface drainwater samples is 0.78, with a standard deviation of 0.63 (fig. 25). The maximum B/Cl ratio of 3.07 is about four times greater than the median ratio. Similarly, the maximum-to-median relation for Se/Cl (0.073 to 0.02) is close to four. Differences between the minimum B/Cl and Se/Cl ratios and their respective median ratios, however, reflect the effects of redox conditions on the solubility of selenium. Whereas the median B/Cl ratio is about four times greater than the minimum ratio (0.78 to 0.2), the median Se/Cl ratio is nearly 70 times greater than the minimum (0.02 to 0.0003). This difference between boron and selenium might be attributable to the "removal" of selenium (as selenite) under reducing conditions by adsorption to fine sediments.

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Several fields seem to be sources of boron, as indicated by B/Cl ratios of 3.07 for site 57, TD-2554, and 2.0 for site 44, S-230. Site 57 is in the middle, north to south, of the Imperial Valley and on its eastern border. There is nothing particularly outstanding about the chemistry of subsurface drainwater at this site nor any indications of geothermal activity that might account for the higher boron concentrations. The median B/Cl (× 1,000) ratio in monthly samples from the East Highline Canal (Colorado River water) is 1.54.

Figure 25. Boron to chloride ratios in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Interaction of Subsurface Drainwater and Shallow Ground Water

An evaluation of the interaction of subsurface drainwater and shallow ground water is helpful in estimating the relative contribution of each source to subsurface drain flow. Subsurface drainwater is defined here as water from land surface to a depth of about 6 ft. Shallow ground water is water from about 6 ft below land surface to a depth of several hundred feet. As discussed in the earlier "Hydrology" section, Tod and Grismer (1988) showed that in clayey soils there was little percolation of irrigation water past the subsurface drains. To explore the relation between shallow ground water and subsurface drainwater, 3 fields were selected from the 15 where soil samples and monthly subsurface drainwater samples were collected. These sites were selected to be areally representative of the Imperial Valley and, also, to cover a wide range in selenium concentration. Multiple-depth wells and lysimeters were installed at each site to determine the chemistry of shallow ground water. Water samples collected from these wells and lysimeters were analyzed for a large number of chemical constituents, including hydrogen and oxygen isotopes, selenium, nitrogen species (ammonia, nitrate + nitrite, N-15/N-14), iron, manganese, boron, sulfur (S-34/S-32), dissolved solids, and tritium. Dissolved selenium, chloride, and sulfate were determined on pore water extracted from core samples collected during drilling.

Samples for analysis of hydrogen and oxygen isotopes were collected to determine the source of shallow ground water in the nested wells and lysimeters. Results of these analyses are shown in figure 26, where δD and $\delta^{18}O$, in permil, are plotted against the meteoric water line. Two measurements of Salton Sea water from Craig (1966) are included to show any major changes with time. The δD and $\delta^{18}O$ of these samples increase with distance from the mouth of the river toward the center of the sea where the water has undergone more evaporation. Concentrations of hydrogen and oxygen isotopes (shown in fig. 26) also were determined from samples collected from the Salton Sea during this study. In addition, the δD and $\delta^{18}O$ of water in Lake Mead, the source of Colorado River water used for irrigation in the Imperial Valley, is shown (concentrations are -114 and -14.5 permil, respectively). The evaporation line clearly passes through samples from the Salton Sea and Lake Mead; the line also represents the best fit for shallow ground water at the three nested-well and lysimeter sites. The relation shown in figure 26 clearly demonstrates that shallow ground water at these three sites, ranging in depth from 6 to 199 ft below land surface, originates from the Colorado River. The slope of the regression line is 5.9, which compares favorably with the slope of 5.4 for subsurface drainwater in the Imperial Valley and indicates that evaporative concentration of Colorado River water also produced the shallow ground water.

FIGURE 26 near here

Figure 26. Regression plot of hydrogen and oxygen isotopes and the meteoric water line for water samples from wells and lysimeters at three sites in the Imperial Valley.

Stable-isotope concentrations also can provide an indication of the effects of soil type on the movement of water beneath a field by showing the degree to which evaporative concentration occurs. Composition of soils at the southern site, S-371, is 70 percent Imperial-Glenbar silty clay loam, wet; 20 percent Meloland very fine sandy loam, wet; and 10 percent Holtville silty clay, wet (Zimmerman, 1981). Loam soils, by definition, have less than 52 percent sand. Sandy soil at the southern site compared to clayey wet or clayey saline soil at the northern and middle sites would be expected to allow deeper infiltration of irrigation water and thus less evaporative concentration in the shallow ground water. Water samples from the two lysimeters at depths of 12 and 18 ft and from the shallow well at 23 ft indicate that little evaporative concentration has occurred (δD of -99.5, -102, and -103.5 permil, and $\delta^{18}O$ of -12.2, -12.1, and -13 permil, respectively). However, as discussed in "Selection of Sampling Sites," the lysimeters are located in an area strongly affected by tailwater runoff. Comparison of dissolved-solids concentration for these three samples (2,140, 1,350, and 1,450 mg/L) with the dissolved-solids concentration in the subsurface drainwater from the sump (9,170 mg/L average for 12 monthly samples) seems to indicate that the water in the lysimeters and shallow well (at depths of 12 to 23 ft) is not the same water that occurs in the subsurface drains at the site. At a depth of 39 ft, however, higher (less negative) δD and $\delta^{18}O$ values (-96 and -11.35 permil) indicate that evaporation has occurred. This trend of increasing δD and $\delta^{18}O$ with depth continues to 84 ft, where δD was -84 and $\delta^{18}O$ was -9.0 permil. These ratios can be compared with those for subsurface drainwater in S-371, in which δD and $\delta^{18}O$ were -98 and -11.7) permil, respectively (average for 12 monthly samples).

Although water at depth is more evaporative than water immediately beneath land surface, water from the deeper wells at the southern site plot toward the lower end of the regression line shown in figure 27. Tritium concentrations confirm that water from land surface to a depth of 23 ft is recent irrigation water. At 12.5, 18, and 23 ft, the tritium concentrations were 28.9, 28.9, and 27.7 TU's (tritium units), respectively. These concentrations are similar to current Colorado River tritium concentrations of 30 TU's (fig. 28). As depth increases, tritium concentration decreases to 3.6 TU's at 39 ft, 2.1 TU's at 49 ft, and 0.4 and 0.8 TU at 65 and 114 ft, respectively. Water 65 ft and deeper is effectively tritium dead, indicating a pre-1952 source. Isotopically, this deeper water is derived from the Colorado River. Historically, periodic flooding of the Salton Trough by the Colorado River has resulted in the formation of a series of lakes. These lakes ranged in size from Lake Cahuilla, which 40,000 years before present had a shoreline altitude of 160 ft above sea level, to lakes the size of the current Salton Sea or smaller. Partially evaporated water from this episodic flooding is trapped at different depths in the sediments of the Imperial Valley. Recharge from the All American canal also is a source of local ground water, but does not effects the geohydrology of the system below 100 ft (Loeltz and others, 1975).

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Figure 27. Tritium concentration in water samples from lysimeters and wells at selected fields in the Imperial Valley.

Figure 28. Tritium concentration in water samples from the Colorado River, 1960-88.

The δD and $\delta^{18}O$ of shallow ground water at the northern site, drained by sump 417, indicate that the water is highly evaporated. The δD and $\delta^{18}O$ at a depth of 8 ft was -80.5 and -8.1 permil, respectively. Although specific conductance was 70,000 μS/cm at 8 ft and peaked at 84,000 μS/cm at 14 ft, δD and $\delta^{18}O$ reached their maximum ratios of -59.5 and -5.15 permil, respectively, at 34 ft below land surface (fig. 29). This shift in the relation between specific conductance and hydrogen and oxygen isotopes may be due to dissolution of evaporative salts deposited by historical lakes that occupied the Salton Trough. The northern site is toward the deeper part of the Salton Trough, where evaporative salts would have been deposited. Finer grained sediments from inflowing water also would be deposited in these low-lying areas. The Soil Conservation Service (1982) has classified soils in this area as Imperial silty clay, wet. The effect of these clayey soils on water quality beneath the northern-site fields can be shown by comparing the isotopic ratios with those from the southern site. Higher evaporation at the northern site is indicated by more positive δD and $\delta^{18}O$ ratios (fig. 26), as well as by higher specific conductance, beneath land surface (fig. 29).

FIGURE 29 near here

Figure 29. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the northern site (near S-417) in the Imperial Valley.

Water from the deepest well (199 ft) at the northern site is isotopically similar to water at 8 ft, but the dissolved-solids concentrations differ considerably. Dissolved-solids concentration at 8 ft was 57,300 mg/L (at a δD of -80 permil and a $\delta^{18}O$ of -8.1 permil), but at 199 ft the concentration was 13,800 mg/L (at a δD of -78 permil and a $\delta^{18}O$ of -8.0 permil). Again, these differences in dissolved-solids concentration for water having the same isotopic ratios probably are due to the dissolution of evaporative salts or to the operation of different mechanisms of concentration: (1) evaporation of irrigation water in a shallow system, and (2) historical concentration in underflow and (or) older lake water in the regional ground-water system. The source of the water at both depths clearly is the Colorado River (fig. 26). Additionally, the isotopic composition of the water at 34 ft, where δD equaled -59 permil and $\delta^{18}O$ equaled -5.2 permil, closely matches the composition (-60 and -5.2 permil) of water in the Salton Sea as determined by Craig in 1966 (Craig, 1966). The dissolved-solids concentration of these two samples (the 34-ft sample and Craig's sample) also is similar (both about 34,000 mg/L). In a manner similar to that at the southern site, dissolved-solids concentration at the northern site decreased with depth to an apparent regional level of 13,800 mg/L at 199 ft.

Sandier soils at the southern site, in comparison with those at the northern site, allow for deeper penetration of recently applied irrigation water. The clayey soils at the northern site preclude significant penetration. Water from the upper lysimeter at the northern site at a depth of 8 ft had a tritium concentration of 33 TU's. At 14 ft, however, the tritium concentration decreased to 6.5, at 19 ft to 4.8, and (in the shallow well) at 34 ft to 2 TU's. The tritium concentration at 8 ft indicates recent irrigation water; concentrations at 14 ft and below indicate that only a minor amount of recent irrigation water reaches that depth and mixes with native water of pre-1952 origin. These low tritium values also might be the result of incomplete well development in clay-rich soils. Water in sump S-417, which drains the field at the northern site, had a tritium concentration of 29.2 TU's, equivalent to recent Colorado River water.

The middle site, drained by sump S-154, is located in an area that in 1902 was identified as Mesquite Lake (Holmes, 1903). In the early 1900's the Alamo River (at that time called the Salton River) flowed north from the international boundary to Mesquite Lake in an area of high-alkali soils about 3 mi northeast of the town of Imperial (Holmes, 1902, p. 1238). The Soil Conservation Service in a recent (1982) soil survey, classified the soil in this area as Imperial silty clay, saline. This is the only area in the Imperial Valley, not under water, where the soil is designated as saline. Hydrogen- and oxygen-isotope ratios in water samples collected from nested wells and from lysimeters at this site plot on the evaporative concentration line shown in figure 26, indicating that water at the middle site also is derived from the Colorado River. The median δD and $\delta^{18}O$ values of -87 and -9.1 permil fall between the medians from the southern and northern sites of -96 and -11.35 and -68 and -6.5 permil, respectively. Although not as highly evaporated as at the northern site, water at the middle site nevertheless has high dissolved-solids concentrations (for example, 49,500 mg/L at a depth of 9 ft) (fig. 30). Water beneath the middle site also has a higher ratio of dissolved-solids concentration to δD than water at the northern site. Because this middle-site field is in a localized topographic depression and fairly recent (early 1900's) lakebed, evaporative salts present in the soils may be leached by heavy flushing of the field necessary to make a suitable environment for growing crops. In spite of the added salt input from dissolution of evaporated salts present in the soils, the correlation of $\delta^{18}O$ with dissolved-solids concentration, $100 \times r^2$ of 87, is excellent. The less highly evaporated water (with a δD of -87.5 permil and a $\delta^{18}O$ of -9.35 permil) is in the deepest well (at 75 ft). In a manner similar to that at the northern and southern sites, the dissolved-solids concentration at the middle site decreases with depth and approaches a regional level of about 13,000 mg/L.

FIGURE 30 near here

Figure 30. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the middle site (near S-154) in the Imperial Valley.

The effect of these clayey soils on movement of water beneath the field is more pronounced at this site than at either the northern or southern sites (fig. 27). Tritium concentrations in water from lysimeters and wells beneath the middle site indicate that no recent irrigation water percolates past a depth of 14 ft. Insufficient water was available from the lysimeter at 9 ft for sample analysis. The tritium concentration at 14 ft was 0.6 TU's, indicating no recent water present. Very low levels of tritium were detected in the samples from 40 and 55 ft, 1.7 and 2.3 TU's, respectively; however, these concentrations are believed to be artifacts from drilling (incomplete well development). Tritium concentration in the sump draining the middle site was 33.4 TU's, a little greater than present-day Colorado River water.

The use of elemental ratios such as Se/Cl in demonstrating the similarity of subsurface drainwater in the Imperial Valley is not applicable to most ground-water samples collected during the study. Reducing conditions at depth may transform the selenium present as SeO_4^{-2} to SeO_3^{-2} or HSe^- and H_2Se^0. The reduced compounds can be adsorbed onto the soils and control the Se solubility (Neal and others, 1987) (Elrashidi and others, 1987). Reducing conditions at depth are present at all three nested-well and lysimeter sites, generally decreasing the usefulness of Se/Cl ratio comparisons; however, the comparisons do show the probable removal of Se in ground water.

Shallow-ground-water chemistry at the three nested-well and lysimeter sites demonstrates the effects of the ongoing chemical, biological, and geohydrological processes beneath the fields. These reactions occur under a variety of redox conditions, as shown by the relation between selected constituents. Because artesian conditions are present throughout much of the Imperial Valley, shallow ground water represents a potential source of discharge to either the subsurface drains or the drainage ditches, and therefore to the Salton Sea, the terminus of these drains and ditches.

The quality of water in the nested wells and lysimeters at the northern site changes significantly with depth. As discussed in the previous paragraphs, dissolved-solids concentration increases immediately beneath the field--followed by an overall trend (exception noted below) of decreasing concentration with depth. Chloride concentrations are synchronous with this pattern (fig. 29). Dissolved-solids concentration, in an exception to the trend, shows a small increase at 75 ft. This increase in concentration from 25,700 mg/L at 54 ft to 31,200 mg/L at 75 ft is the result of an increase in sulfate ion from 3,800 to 6,800 mg/L. The sulfate increase is accompanied by an increase in magnesium and sodium concentrations from 5,400 to 6,800 mg/L (Mg) and 1,500 to 1,700 mg/L (Na).

The well at 75 ft is perforated in a sandy layer several meters thick that is overlain and underlain by very tight clays. Artesian conditions are present in this zone--which is supersaturated with respect to carbon dioxide. The carbon dioxide effervesces on exposure to the atmosphere, and calcite forms in the bottom of the sample bottle (the precipitate bubbles on addition of acid). This sandy layer at 75 ft most likely has some continuity with the carbon dioxide-emitting mud volcanoes along the southeastern edge of the Salton Sea. According to Loeltz and others, 1975, "the small carbon dioxide emitting domical hills in the Obsidian Butte area are formed by rising thermal water and mud highly charged with carbon dioxide." Water at depth in the geothermal system (brines) are high in sodium, calcium, potassium, boron, lithium, barium zinc, lead, and copper (Helgeson, 1968, p. 131). Perhaps, some influence of the geothermal system is seen in water from the artesian zone.

Water-quality analyses indicate that the artesian zone apparently affects water in the overlying zone. Another possible explanation, however, is contamination of the upper wells as a result of incomplete seals in the annulus of the hole. Each well was perforated, in a 5-foot interval, at the bottom of the PVC and the annulus was packed with sand. The interval to the next well point was sealed with bentonite chips. Water from this highly pressurized system might force its way through the well seal, thereby contaminating the other well.

The effects of reducing conditions on concentrations of selenium and other redox sensitive constituents in shallow ground water is shown in figure 29. Examined were the constituents selenium, ammonia, nitrate, and iron, along with pH. Selenium concentrations at the northern site increased beneath the field from 24 μg/L at 8 ft and 20 μg/L at 14 ft to 90 μg/L at 19 ft. This increase shadows the dissolved-solids concentration even though selenium is strongly correlated with dissolved solids in subsurface drainwater ($100 \times r^2$ equals 70.5). Below 19 ft, selenium concentration decreases to 4 μg/L at 34 ft, 1 μg/L at 54 ft, and less than 1 μg/L at 75 and 199 ft. This decrease in selenium concentration corresponds to an increase in ammonia concentration. The increasing presence of ammonia indicates that a reducing environment is becoming more pronounced with depth. Under reducing conditions, nitrate is converted to ammonia, and selenate can be converted to selenite, elemental selenium, or selenide, depending on the environmental conditions (soil acidity or alkalinity, pH, pE, and biota present). At 75 ft, the nitrate concentration is less than 0.1 mg/L, and the ammonium concentration has increased to 21 mg/L. Concomitant with the increase in ammonia concentration is an increase in iron concentration from 340 μg/L at 54 ft to 23,000 μg/L at 75 ft. The high iron and ammonium in concert with the less-than-detection-level nitrate and selenium indicate a reducing environment. According to Elrashidi and others (1987), "Under highly reducing conditions, selenides are the major inert sink of Se introduced into the environment. Contamination of waters or soils by these minerals poses a minimal hazard of Se toxicity so long as their depository remains reduced." Concentrations of manganese ranged from 210 μg/L at 199 ft, where reducing conditions prevailed, to 11,000 μg/L at 14 ft, where selenium and nitrate still were present.

Of particular interest was the finding of elevated levels of arsenic at depth in the Imperial Valley. In reconnaissance investigation of the Salton Sea area, elevated levels of arsenic were not found in either subsurface drainwater or in bottom sediments. (Median arsenic concentration in bottom sediments was 5.6 mg/kg, in comparison with the maximum baseline concentration for 95 percent of soils in the Western United States of 22 mg/kg; and arsenic concentration in subsurface drainwater ranged from 1 to 4 μg/L, considerably less than the 50 μg/L criterion (U.S. Environmental Protection Agency, 1986) for protection of aquatic life.) In this detailed study, arsenic concentration in shallow ground water at and above 54 ft ranged from 2 to 9 μg/L. At 75 ft, however, the concentration increased to 91 μg/L, representing an order-of-magnitude increase. The concentration at 199 feet was 67 μg/L. The source of this arsenic is unknown at this time. There is some moderate geothermal influence at these depths that might account for this increase. According to Welch and others (1988), "Geothermal water generally has higher arsenic concentrations than non-thermal ground water with the highest concentrations found in brines such as those found in the Salton Sea geothermal area." Water temperature increases with depth from 30 °C at 54 ft to 31.5 °C at 75 ft and 36 °C at 199 ft. The wells at 75 and 199 ft are artesian and likely have continuity with the carbon dioxide-producing system along the southeastern edge of the Salton Sea.

There are several similarities in the patterns of chemical concentrations between the northern and middle sites (fig. 30). Although there is no increase in dissolved-solids concentration beneath the middle-site field such as that observed at the northern site, major ion constituents are elevated. Dissolved solids presents a pattern of decreasing concentration with depth. At 9 ft, the concentration is 49,500 mg/L, decreasing to 13,200 mg/L at 71 ft. The wells at 71 and 95 ft are artesian, but do not present the major compositional changes in ion chemistry that were observed for the two artesian wells at the northern site. In the two artesian systems (at the northern and middle sites), sodium and sulfate concentrations, in comparison with concentrations at 55 ft, continue to increase with depth.

Concentrations of constituents indicative of redox conditions also exhibit a pattern similar to that of the northern site, though not quite as strongly reducing in the deeper wells (fig. 30). Selenium and nitrate concentrations decrease with depth. Regression of selenium against nitrate yields a $100 \times r^2$ of 93, indicating that similar processes affect both selenium and nitrate. Ammonia, another indicator of redox conditions, does not present any clear pattern in concentration. The ammonia concentration at 9 ft is 1.6 mg/L, increasing to 5.6 mg/L at 71 ft and 3.6 mg/L at 95 ft. In comparison with ammonia concentrations of 21 and 28 mg/L for the deepest wells at the northern site, these ammonia concentrations do not indicate strong reducing conditions. Nevertheless, by 55 ft, both selenium and nitrate have been reduced to below detection levels, less than 1.0 μg/L and 0.1 mg/L, respectively. In a manner similar to that of the northern site, iron concentration in the two artesian zones is indicative of reducing conditions. Iron concentration increased from 310 μg/L at 55 ft to 6,400 μg/L at 71 ft and 6,000 μg/L at 75 ft.

The patterns of arsenic concentration with depth also were analogous to those at the northern site. The shallow-depth lysimeters and wells had low arsenic concentrations that ranged from 2 to 7 μg/L. The two deeper wells in the artesian zone had concentrations of 46 and 59 μg/L at 71 and 95 ft, respectively. Unlike the northern site, where a thermal gradient is present that might indicate geothermal influence, no such temperature gradient is apparent at the middle site. Although the geothermal gradient decreases quickly south of the northern site, other thermal anomalies are present in the southern Imperial Valley that could influence the temperature gradient (Helgeson, 1968, p. 158).

Few similarities are present in the magnitude and pattern of elemental concentrations in water samples collected from the southern site and those from the northern and middle sites. As discussed in "Selection of Sampling Sites," the placement of lysimeters and wells at the southern site was not suitable to obtain water samples indicative of irrigation drainage from the field drained by S-371. These wells and lysimeters receive water from a variety of sources, including the drainage ditch, the irrigation canal, and possibly surface-water accumulations. Water from the lysimeters also is of questionable validity because of the collapsing of the holes during drilling as a result of the high water content and coarse nature of the soils. The profile of dissolved-solids concentration shows an apparent increase with depth from a low of 2,140 mg/L at 12.5 ft to a high of 15,000 mg/L at 49 ft, followed by a gradual decline to a regional level of 9,620 mg/L at 114 ft (fig. 31). Although lysimeters were placed at 4 and 7 ft, no water was present at any time during sampling. However, there seems to be continuity in the pattern of Cl/SO_4 and Cl/Na ratios on either side of the ditch for the samples collected at 18 ft (lysimeter) and 23 ft (well). The lysimeter probably is affected more by tailwater runoff than by drainage from the field.

FIGURE 31 near here

Patterns in concentrations of redox-indicating species in water from the nested wells and lysimeters at the southern site are markedly different from patterns at the northern and middle sites (fig. 31), primarily because water in the lysimeters and shallow wells at the southern site was strongly influenced by tailwater runoff and by the irrigation canal. Additionally, there is no apparent pattern to concentrations of these species with depth. Therefore, no analysis of changes in concentration of redox-sensitive species is presented for this site.

Figure 31. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the southern site (near S-371) in the Imperial Valley.

Movement and Partitioning of Selenium in the Salton Sea

As discussed previously, selenium originates at low levels in irrigation water; concentrates by evaporation in the fields of the Imperial Valley to levels as high as 360 $\mu g/L$; and is transported to the Salton Sea by the New and Alamo Rivers, as well as by several drains, that discharge directly to the sea. From a discharge-weighted concentration of 25 $\mu g/L$, selenium in subsurface drainwater is diluted by low-concentration tailwater and canal seepage to concentrations of 4 and 8 $\mu g/L$ in the New and Alamo Rivers at their outlets to the Salton Sea. Samples collected in the delta of the Alamo River and in the Salton Sea indicate that this inflowing selenium is being removed from the water. The understanding of the selenium-removal process has been accelerated as a result of the detection of selenium contamination at major irrigation drainwater projects--such as Kesterson National Wildlife Refuge (California), Stillwater Wildlife Management area (Nevada), Stewart Lake Waterfowl Management Area and Ouray National Wildlife Refuge in the Middle Green River basin (Utah), and Kendrick Reclamation Project area (Wyoming)--and by the research generated from concern about this contamination.

Previous studies (Cook and Bruland, 1987) indicated that the main selenium-removal process centered around the incorporation of selenium into biological particles that settle to the bottom of the water body and degrade, releasing dimethyl selenide. This degassing of dimethyl selenide was one mechanism considered, along the settling of the selenium-containing biota, to explain selenium removal from the water column. In this degassing mechanism, selenium is an analog for sulfur. Current research, however, indicates that the removal rates engendered by these processes are not sufficient to account for the magnitude of selenium removal in water bodies such as the Salton Sea (Oremland and others, p. 1163, 1990). This research has identified a sulfate-independent process whereby selenate is reduced to elemental selenium by anaerobic bacteria (Oremland and others, p. 2340, 1989). These bacteria use selenate as a preferential electron acceptor. Nitrate acts as a competitive electron acceptor that interferes with this biochemical reduction of selenium. Although selenate is removed from the water, this removal does not necessarily mean that selenium is no longer a contaminant. According to Oremland (1990),

> The fact that this occurs independently of the abundant molecular analog (for example, sulfate) allows for the reaction to be the major selenium sink in the presence of high dissolved sulfate (about 300 millimoles). Nonetheless, we hypothesize that accumulation of elemental Se in surficial sediments of impacted regions does not necessarily remove this toxicant from the food chain. Ingestion by sediment-feeding organisms, as well as oxidation or further reduction by chemical or biological means will still pose a threat to the ecosystem.

Water-quality sampling in the delta area of the Alamo River was done to determine type and location of the interface between the river and the sea and the partitioning of selenium between the water and sediment. Water and bottom-sediment samples were collected and specific conductance, temperature, pH, and dissolved-oxygen were measured in August 1988, February 1989, and August 1989. No bottom sediments, however, were analyzed for the August 1989 sampling. Sampling-site locations are shown in figure 32. Because the detection limit for aqueous selenium is 1 $\mu g/L$ and the selenium concentration in the Salton Sea is about 1 $\mu g/L$, little information about selenium processes can be determined from any areal water sampling of the Salton Sea.

GURE 32
near here

Figure 32. Areal distribution of selenium in bottom sediments at the southern end of the Salton Sea.

Specific-conductance values, along with concentrations of selenium, indicated the presence of a narrow zone of mixing between high-salinity Salton Sea water and low-salinity river water. This mixing zone was located at site 10 (see fig. 32) about 200 ft seaward of the end of the levee on the left bank of the Alamo River. Water at this site was less than 3 ft deep. The specific conductance at a depth of 1.3 ft was 5,000 μS at a temperature of 30.9 °C and a dissolved-oxygen concentration of 4.2 mg/L (saturation 56 percent). At the bottom, at a depth of about 3 ft, the specific conductance was 51,000 μS at a temperature of 30.3 °C and a dissolved-oxygen concentration of 1.2 mg/L (saturation 18 percent). The selenium concentrations were 8 μg/L at 1.3 ft and less than 1.0 μg/L at 3 ft. These data indicate that the relatively high-selenium river water is mixed with and diluted (with respect to selenium concentration) by the low-selenium Salton Sea water--and, conversely, the low-salinity river water is concentrated (with respect to salinity) by the high-salinity water of the Salton Sea. The few samples collected in this study indicate that selenium in the Alamo River, on the river side of the interface (between sites 9 and 10), is a mixture of selenate and selenite. The total-selenium concentration measured at this site during this limited June 1989 sampling was 6.35 μg/L, with 2.56 μg/L as Se(+IV) and 3.79 μg/L as Se(+VI). These concentrations show that a significant portion of the selenium flowing into the Salton Sea is in reduced form. At the interface (site 10), total selenium is below the detection level of 2.4 μg/L; Se(+IV) is 1.79 μg/L; and Se(+VI) is below the detection level of 0.2 μg/L.

The water-quality measurements made throughout the delta indicate that some stratification is present in the water column. Dissolved-oxygen saturation indicates a eutrophic system where oxygen saturation is greater than 100 percent during daylight hours. The night of August 24, 1988, a tropical storm swept through the Imperial Valley carrying high wind and heavy rainfall. Although the prevailing winds are out of the northwest, winds in this storm were from the southwest. Observations made the morning of August 25, 1988, indicated that algal mats from the embayments on the southern end of the Salton Sea were carried toward the main body of the sea. As the prevailing winds reestablished, a ring of dead fish was observed off the delta of the Alamo River. Measurements of dissolved-oxygen concentration during the morning of August 25th revealed saturations that were substantially lower than those normally observed (less than 30 percent of normal) during daytime sampling. Conditions returned to normal later on August 25th as the prevailing northwest winds blew the algal mats back into the embayments on the southern end of the Salton Sea. Bottom sediments in the southern end of the Salton Sea are anaerobic. These sediments stirred up by the storm exerted an immediate oxygen demand on the overlying water column, resulting in lowered levels of oxygen saturation. To demonstrate this effect, dissolved-oxygen concentration was measured, at site 17 on February 16, 1989, and found to be 35.6 mg/L, giving a saturation of 356 percent. The bottom sediments then were agitated, using a paddle from the airboat, and dissolved-oxygen concentration was remeasured. The remeasurement indicated that dissolved-oxygen concentration had decreased to 21.1 mg/L and saturation had decreased to 214 percent.

Measurements made during the winter indicate large-scale changes in water temperature, but the remaining properties and constituent concentrations were the same as during summer. The mixing zone was located in the same area, although the depth was only 2 ft. Specific conductance at the surface was 7,400 μS, with a dissolved-oxygen concentration of 12.2 mg/L (saturation 112 percent) and a selenium concentration of 8 μg/L. Near the bottom at 2 ft, the specific conductance ranged from 34,000 to 40,000 μS, with a dissolved-oxygen concentration of 21.9 mg/L (saturation 210 percent).

Bottom-sediment samples were collected at sites throughout the Alamo River delta. Results for these samples are presented as total-selenium concentration, in milligrams per kilogram or parts per million. Selenium concentrations in bottom sediments from the Alamo River were 0.2 mg/kg at site 1 (Garst Road) and 0.3 mg/kg at site 2 (see fig. 32). At the remaining delta-area sites, selenium concentration in the bottom sediments ranged from 0.3 to 2.5 mg/kg. Although two adjacent sites in an embayment had relatively high selenium concentrations, 1.3 and 2.5 mg/kg, there was no apparent pattern to the areal distribution.

EFFECTS OF SELENIUM AND OTHER CONSTITUENTS ON BIOTA

Selenium

The agricultural use of irrigation water has contributed to the enrichment of selenium in water, sediment, and biota throughout the Imperial Valley (Setmire and others, 1990). Selenium also has been detected at elevated levels at many other agricultural drainwater projects throughout the Western United States. When found in excessive amounts, selenium is of concern because it has been linked directly to lethal and sublethal effects on fish and wildlife (Ohlendorf and others, 1986).

One of the most important factors of selenium toxicity in aquatic systems is the ability of aquatic organisms to accumulate selenium at concentrations much greater than concentrations in water, sediment, or food items. This extensive bioaccumulation results because selenium is an essential micronutrient and is chemically similar to sulphur (Lemley & Smith, 1987). Bioaccumulation of selenium in birds from elevated dietary levels has been found to impair reproduction (Ort and Latshaw, 1978; Eisler, 1985; Heinz and others, 1987; Ohlendorf, 1989). Field studies in areas of selenium-laden agricultural drainwater have shown embryonic mortality and deformities in water birds attributable to the adverse effects of selenium (Ohlendorf and others 1986a, 1986b; Schroeder and others, 1988). One of the primary objectives of this study was to determine if selenium-enriched irrigation drainwater was causing adverse biological effects, such as impaired reproduction in water birds at the Salton Sea.

TABLE 9 near here

Selenium concentrations in biotic samples collected from the Salton Sea area during 1988-90 are summarized in table 9. Although selenium was found at all trophic levels, concentrations tended to increase with increasing trophic level, indicating biomagnification. Biomagnification is the process in which a contaminant, such as selenium, is accumulated by lower level organisms in the food chain and increases in concentration as it is passed up the chain when higher organisms feed on lower organisms. This magnification is due to the increased energy needs and inefficiency of energy transfer from one trophic level to the next higher level, which can result in an imbalance between contaminant intake and elimination. Recent studies on fish (Lemly and Smith, 1987) show that biomagnification of selenium does occur in aquatic food chains.

The general trend of higher selenium concentrations in biota from the Salton Sea in comparison with concentrations in river/drain sites was similar to the trend found in bottom-sediment samples (Setmire and others, 1990). As reported in Eisler (1985), this trend also may be due, in part, to the finding that higher selenium concentrations are found in estuarine and marine organisms than in freshwater organisms. Limited sampling in areas not affected by agricultural drainwater, such as San Felipe and Salt Creeks, indicates the presence of significant local sources of selenium for bioaccumulation in plants and fish (table 9).

Aquatic Vegetation

Algae.--Selenium in algae throughout the Salton Sea had the lowest concentrations of all biota sampled, (table 9). Although there were some species differences between mean selenium concentrations, most were below normal algae concentrations of 1.0 µg/g DW (Ohlendorf, 1989). Comparisons of green filamentous algae from Salton Sea with other locations (table 10) show that selenium concentrations are above those of Volta WMA (reference site), comparable to those of another drainwater site (Fernley WMA), and well below those of a highly contaminated drainwater site (Kesterson Reservoir).

TABLE 10 near here

Emergent Vascular Plants.--Cattail was the only vascular plant sampled during this study. Selenium concentrations in cattails from three agricultural drains were below detection limits. However, selenium was detected at a low level (1.1 µg/g) in cattails from one of two creeks not heavily affected by drainwater (table 9). Comparisons of Salton Sea data with data from other areas (table 11) show that selenium concentrations in cattail from these two creeks are below the 1 µg/g DW normal level (Ohlendorf, 1989), and well below Kesterson NWR values.

TABLE 11 near here

Aquatic Invertebrates

Marine invertebrates.--Invertebrates collected from the Salton Sea had selenium concentrations ranging from 0.8 to 12.1 μg/g DW (table 9). Pileworms had a higher mean selenium concentration than pelagic invertebrates such as waterboatmen. Also, a comparison of the highest selenium concentrations shows pileworms to be about four times higher than pelagic invertebrates. This difference can be explained by the substantially higher selenium concentration in sediment where the pileworms reside as contrasted to very low concentrations in the water column, the habitat for pelagic invertebrates.

TABLE 12 near here

Selenium concentrations in waterboatman (table 12) were lower for the Salton Sea in comparison with another drainwater-impacted area (Fernley WMA), much lower in comparison with a heavily impacted area (Kesterson NWR), but slightly higher in comparison with a reference area (Volta WMA). (In this report a reference area is defined as an area not affected by agricultural drainwater.) Waterboatman is an important food resource consumed by a variety of birds, including the resident black-necked stilt; therefore, selenium would be expected to bioaccumulate in Salton Sea birds above levels found at reference areas, but well below those found in areas heavily impacted by drainwater.

Freshwater Invertebrates.--Mean concentrations for crayfish and Asiatic river clams (table 9) were close to or below values (about 4 μg/g DW) generally detected in freshwater invertebrates (Ohlendorf, 1989). Asiatic river clams collected from five different drains had a mean selenium concentration of 4.4 μg/g WW and a range of 2.6-6.4.

Comparable selenium data for freshwater mollusks are scant in the literature. A study by Winger and others (1984) documented selenium bioaccumulation in Asiatic river clams from the Apalachicola River in Florida; the concentration of 0.7 μg/g WW is comparable to concentrations of 0.8 and 0.6 μg/g WW in the Wister and Johnson Drains in the Salton Sea area. Auti Not ref./

Clams from the Wister Wildlife Management Area and Johnson Drain had the lowest selenium concentrations (2.9 and 2.6 μg/g DW), and those in the Trifolium Drain and New River had the highest concentrations (6.3 and 6.4 μg/g DW). These results show that clams from major drains and rivers affected by significant drainwater inflow are bioaccumulating selenium above the 4 μg/g value typically found in freshwater invertebrates (Ohlendorf, 1989); in contrast, clams in areas with minor drainwater inflow had concentrations below 4 μg/g. Thus, the Asiatic river clam is an excellent selenium biomonitor because it is a permanent sessile benthic resident and it bioconcentrates selenium in relative proportion to drainwater inflow.

In situ bioaccumulation results from the bioassay of transplanted Asiatic river clams are shown in figure 33. During the first 4 months, selenium was bioaccumulated about 1.4 times above the initial concentrations in the Trifolium Drain. Clams collected in the Trifolium Drain in May 1990 showed a slight decrease from initial concentration, and a significant decrease from peak concentrations. Because bioassay clams were not sampled on a more regular basis, it is not known whether selenium concentrations actually decreased or if the May 1990 sample is an outlier. Data from indigenous clams taken from the Trifolium Drain at the same time as the bioassay clams had a selenium concentration of 6.3 μg/g DW. This concentration is lower than the highest concentrations (7.5 μg/g DW) in bioassay clams, but above the May 1990 transplanted-clam concentration of 4.4 μg/g DW. Any future clam bioassays should ensure that sampling is performed on a more frequent and regular basis and that duplicate samples are included to better assess fluctuation in selenium loading and concentrations. Clams from the bioassay in the Alamo River (fig. 33) showed relatively little change in selenium concentration during the first 4 months.

FIGURE 33 near here

Figure 33. Selenium bioaccumulation in transplanted Asiatic river clams, 1989-90.

Fish

Selenium concentrations in fish from various areas within the Imperial Valley are given in table 9. Marine fish from the Salton Sea had significantly higher selenium concentrations than freshwater fish from irrigation drains. Mosquitofish and sailfin mollies from San Felipe and Salt Creeks, not affected by irrigation drainwater, had significantly more selenium than fish from Young, Wister, and Johnson Drains, which have moderate irrigation drainwater inflow. However, data from the Salton Sea reconnaissance investigation (Setmire and others, 1990) show that the mosquitofish and sailfin mollies from Trifolium Drain and New and Alamo Rivers, all of which receive major irrigation drainwater inflow, had selenium concentrations comparable to those in fish from San Felipe and Salt Creeks (table 13). San Felipe Creek, along with major drains and the New and Alamo Rivers, has been shown to have elevated selenium concentrations in water samples (Setmire and others, 1990), in correlation with the higher selenium concentrations in fish.

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A comparison of mosquitofish from Salton Sea area with fish from other locations shows that selenium concentrations in Salton Sea fish were well below concentrations in fish from Kesterson NWR, but above those at Volta WMA (reference area). Selenium concentrations in fish from minor Salton Sea drains were comparable to those in fish from Fernley WMA; fish from Trifolium Drain, which receives major amounts of agricultural drainwater, had the highest concentrations other than fish from Kesterson NWR.

Excessive accumulation of selenium can seriously affect the fishes and sport fishery of the Salton Sea (Saiki, 1990). Among sensitive species, whole-body selenium concentrations greater than 12 μg/g DW may be sufficiently elevated to cause reproductive failure (Lemly and Smith, 1987). Only one sample of a freshwater species, the mosquitofish, collected from the Trifolium Drain was above this threshold. Reproductive failure often is accompanied by deformities in embryos and young. However, no mosquitofish sampled during this study or the reconnaissance investigation showed any signs of deformities. Mean selenium concentration in fish from major agricultural drains, including the Trifolium Drain, of 10.8 μg/g DW (table 12) is well above the lowest concentrations (5-8 μg/g DW) shown to affect reproduction in warmwater fish (Lemly, 1986). It is not known if selenium in major drains has historically or is currently affecting forage-fish populations.

Marine fish from the Salton Sea had whole-body selenium concentrations above the 12 μg/g DW reproductive threshold reported by Lemly and Smith (1987). However, the toxic threshold concentrations for selenium in tissues of marine fishes--such as bairdiella, orangemouth corvina, and sargo--found in the Salton Sea are unknown (White and others, 1987). Although Salton Sea fish contain elevated selenium body burdens, recent observations suggest that they still are able to successfully reproduce (Hagar and Garcia, 1988).

Even though Salton Sea fish generally continue to successfully reproduce, recent data have shown significant decreases in the number of eggs and larvae of two important forage fish, bairdiella and sargo (Matsui, 1989). In addition to this reproductive decline, Matsui also documented deformities in ichthyoplankton that were attributed to ambient contamination. The malformations, that were predominantly retarded cephalic development, have been previously reported following exposure of fish to a variety of anthropogenic contaminants, including pesticides and metals (Matsui, 1989). Selenium is known to cause deformities in fish (Lemly and Smith, 1987) and is above the reproductive threshold of 12 $\mu g/g$ DW in bairdiella; thus, it may be partially or fully responsible for the observed deformities.

Amphibians and Reptiles

Selenium concentrations in two species of herptofauna collected from the New River and several drains are shown in table 9. Levels in whole bullfrogs from the Salton Sea area of 3.6-5.4 μg/g DW were below the 6.2 μg/g DW levels found in bullfrogs (liver tissue) from a "normal" background site in San Joaquin Valley and well below the 45 μg/g DW value found in livers of bullfrogs from San Luis Drain at Kesterson NWR (Ohlendorf and others, 1988). However, selenium is preferentially stored in the liver, and liver concentrations usually are higher than whole-body concentrations. Therefore, Salton Sea bullfrogs probably have selenium levels that are above normal values, but still well below levels found in bullfrogs from highly contaminated sites.

Livers of spiny softshelled turtles collected in several drains had selenium concentrations that ranged from 8.0 to 14.0 μg/g DW. No comparable data for selenium levels in turtles were found in the literature. However, mean selenium levels in Salton Sea area turtle livers of 10.3 μg/g DW were comparable to levels found in gopher snake (*Pituophis melanoleucus*) livers at Kesterson NWR of 11.1 μg/g DW and well above reference levels of 2.1 μg/g DW at Volta WMA and 2.1 μg/g DW in Grasslands Water District (Ohlendorf, 1988). The selenium concentrations found in reptiles at Kesterson NWR were sufficiently high to warrant concern about potential effects in those animals and their predators (Ohlendorf, 1988).

Birds

Effects of selenium bioaccumulation on birds in the Imperial Valley was a major focus of this study. This type of problem was first documented at Kesterson Reservoir in the San Joaquin Valley of California, where selenium from agricultural drainwater bioaccumulated to sufficiently high levels in the food chain to cause mortality and impair reproduction of aquatic birds (Ohlendorf, 1989).

Because the liver is one of the major organs in vertebrates for detoxifying and eliminating selenium, it is the standard tissue for selenium analysis. "Normal" dry weight selenium liver concentrations for freshwater aquatic birds as reported from several field studies is between 4 and 10 μg/g. Results from this study (table 9) show that the northern shoveler, coot, and white-faced ibis all had some liver concentrations above the "normal" value, and the mean concentration in shovelers (19.1 μg/g DW) was almost twice the normal concentration.

However, the concentrations of selenium in bird livers that can be diagnostic of harm or injury are uncertain. The best information available (Heinz, 1989) indicates that when livers contain about 20 μg/g or more of selenium on a wet-weight basis, heavy exposure has taken place that should be considered a possible threat to survival. Even concentrations as low as 10 μg/g could be harmful to more sensitive species and should be of concern.

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FIGURE 34 & 35 near here

The selenium exposure levels of birds from the Imperial Valley are illustrated, using the preceding information, in figures 34 and 35. Of the birds using the Salton Sea (fig. 34), only the double-crested cormorant and the eared grebe had liver concentrations above the 10 μg/g WW area-of-concern threshold, and no species were heavily exposed (that is, no concentrations were above the 20 μg/g WW heavy-exposure threshold). Of the birds using freshwater habitats within the Imperial Valley, only one species, the northern shoveler, had selenium concentrations above the 10 μg/g WW area-of-concern threshold (fig. 35). On the basis of this analysis, aquatic birds from the Imperial Valley have not been exposed to selenium concentrations sufficiently high to threaten survival of adult birds. However, several species have elevated (area of concern) concentrations that may result in adverse chronic or sublethal effects, including reproductive problems.

Figure 34. Selenium exposure levels in livers of water birds and shorebirds utilizing the Salton Sea.

Figure 35. Selenium exposure levels in livers of water birds and shorebirds utilizing rivers and drains.

Migratory birds.-- Selenium-concentration data for migratory water birds are given in table 9. Of the two waterfowl species, the northern shoveler had higher mean selenium concentrations in liver and muscle, as well as a higher range, than the ruddy duck. There were no comparable data from other studies for ruddy ducks; however, liver data for Salton Sea shovelers (mean concentration, 19.1 μg/g DW) were comparable to data for three other species of dabbling ducks collected from San Joaquin Valley sites contaminated by agricultural drainwater (19.9 μg/g DW) and well above the reference-area value of 8.4 μg/g DW (Presser and Ohlendorf, 1987). Comparisons with historical data collected in the Imperial Valley by Koranda and others (1979) show that selenium levels in shovelers have increased by more than 22 percent (from 15.6 to 19.1 μg/g DW). This demonstrates that northern shovelers wintering at the Salton Sea are accumulating a significant loading of selenium and that buildup in bird livers occurs rapidly after the birds arrive at the sea (7.8 days to reach 95 percent of peak concentration in mallards) and is maintained at an equilibrium in proportion to dietary selenium intake (Heinz and others, 1990). Also, selenium bioaccumulation in waterfowl seems to be increasing over time in the Imperial Valley as selenium loading from agricultural drainwater inflow continues. However, the high levels accumulated at the sea probably could be eliminated (75 percent loss after 2 weeks from a high to a low selenium diet; Heinz and others, 1990) if birds migrating to the northern breeding locations consume low concentrations of selenium in their diet.

Liver selenium concentrations in Salton Sea ruddy ducks collected in the autumn when they arrive, 1 month later, and then again in the spring when they leave were not statistically different (one-way analysis of variance (ANOVA), $F=1.470$, $P< 0.2471$). However, if migratory birds are not sampled within approximately 1 week of arrival at the sea, it is not possible to determine if selenium concentration is being elevated at the sea, or if it already was elevated prior to arrival. Nevertheless, it is apparent that an equilibrium at an elevated level of selenium in ruddy ducks is being quickly established while wintering at the sea. This selenium load may be reduced as birds leave the sea if subsequent diets along the Pacific flyway contain less selenium.

The mean selenium concentration in liver of white-faced ibis collected from south Brawley in the Imperial Valley was 7.4 µg/g DW (table 9), which is comparable to concentrations in livers of ibis from the drainwater-contaminated or influenced Carson Lake, Nevada (10.7 and 8.6 µg/g DW for males and females, respectively, Henny and Herron, 1989). Male birds have higher levels because females excrete selenium via eggs (Margat and Sell, 1979); however, selenium concentrations in ibis eggs from Carson Lake (geometric mean, 1.9-5.4 µg/g DW) did not have any significant effect on hatchling productivity to the age of 7-10 days (Henny and Herron, 1989). Because Salton sea ibis had lower concentrations, it can be concluded that the selenium load they accumulate while overwintering at the sea will not have any immediate adverse reproductive effects at the breeding grounds.

Eared grebe livers from Salton Sea had the second highest mean selenium concentration in biota of 12.7 μg/g DW and levels as high as 35.1 μg/g DW (table 9). The mean value was twice as high as the mean for grebes from uncontaminated areas in the San Joaquin Valley (5.6 μg/g DW), but an order of magnitude below the value for grebes from contaminated sites (Presser and Ohlendorf, 1987). These small fish-eating birds feed on small forage fish such as the mudsucker, which have less selenium (6.1 μg/g DW) than the larger forage fish such as bairdiella (12.9 μg/g DW). This may explain why a larger piscivorous bird from the sea, such as the double-crested cormorant, had twice as much selenium in the liver in comparison with eared grebes.

Resident birds.--Selenium concentrations for three resident Salton Sea birds are given in table 9. Because resident birds are continually exposed to selenium from agricultural drainwater within the Imperial Valley, they represent a "worst case" scenario for several trophic levels. The only nesting species extensively investigated in the Imperial Valley was the black-necked stilt. Selenium in bird eggs strongly predicts embryotoxicity, and the toxicity to avian embryos is one of the most restrictive constraints for managing agricultural drainwater (Skorupa and Ohlendorf, 1991).

Selenium data for eggs show that mean values for the Salton Sea area are comparable to those for Grasslands Water District; somewhat higher than Volta WMA values; but significantly lower than Kesterson NWR values (table 14). The Salton Sea mean value of 4.3 μg/g DW is about 43 percent above the avian contamination threshold of 3 μg/g DW (Skorupa and Ohlendorf, 1991)--although this value was established for nonmarine environments. The distribution of selenium in Salton Sea stilt eggs, however, (fig. 36) indicates that for some levels the probability of embryotoxicity (death or deformity) is greater than 20 percent. For the highest selenium concentration (35 μg/g DW), the probability of embryotoxicity, on the basis of the relation between embryotoxicity and selenium concentration in stilt eggs at Kesterson NWR (Ohlendorf and others, 1986), is about 60 percent. Five other stilt eggs had concentrations greater than 10 μg/g DW, the level at which the minimum probability of hatching failure begins (Ohlendorf and others, 1986). The majority of Salton Sea stilt eggs, however, had selenium values for which predicted embryotoxicity is low (less than 10 percent).

TABLE 14 near here

FIGURE 36 near here

Figure 36. Cumulative distribution of selenium in black-necked stilt eggs from the Salton Sea, 1988-89.

The expected incidence of major external deformities in hatchlings of uncontaminated wild populations of birds is less than 1 percent when selenium in eggs generally is less than 3 or 4 μg/g DW (Ohlendorf and others, 1986a). The incidence of abnormalities observed during 1983 at stilt nests in Kesterson Reservoir, where the mean selenium concentration in eggs was 32.7 μg/g DW, was 16.8 percent (Ohlendorf, 1989). Data for the Salton Sea area indicate that 5 percent of stilt eggs from the Imperial Valley have at least a 10-percent probability of hatching failure or embryotoxicity when the mean selenium concentration is greater than 4.3 μg/g DW. However, an extensive survey of 66 stilt nests at Salton Sea during 1989 revealed no external abnormalities in chicks (R.A. James, U.S. Fish and Wildlife Service, oral commun., 1990), but addled eggs were not examined. A more extensive nesting survey would prove useful better documenting percentages of deformities and (or) embryotoxicity in stilts nesting in the Imperial Valley.

TABLE 15 near here

A comparison of Salton Sea data for black-necked stilt liver (Setmire and others, 1990) with data from other locations (table 15) shows mean selenium levels at Salton Sea to be three times higher than those found at a site not affected by drainwater, Volta WMA, and one-half of the mean reported at Kesterson NWR. The stilt liver concentrations from this study also closely agree with data from 20 stilts collected by California Department of Fish and Game from the Salton Sea in 1986 (White and others, 1987). These values were all below the 20 μg/g WW heavy-exposure threshold reported by Heinz (1989).

In contrast with stilts, mean selenium concentration in coot livers (table 9) collected in 1989 was within the 4 to 10 $\mu g/g$ DW "normal" range found in freshwater birds (Ohlendorf, 1989). Salton Sea coot liver concentrations for 1986 samples (Setmire and others, 1990) were slightly higher than those for 1989. A comparison of coot liver selenium data (table 16) shows that the Salton Sea mean concentration is about twice as high as that for Volta WMA but only about one-seventh the concentration for coots from the heavily contaminated Kesterson NWR. Even though selenium concentrations in Salton Sea coots are higher than those for areas not affected by agricultural drainwater, the concentrations generally are within "normal" ranges and well below any values shown to cause toxicosis in wild aquatic birds (Ohlendorf and others, 1988).

GURE 16 near here

Endangered birds.-- An endangered Yuma clapper rail salvaged from the southeast Salton Sea at Wister WMA had a whole-body selenium concentration of 4.8 $\mu g/g$ DW. This is within the range carcasses from Yuma clapper rails salvaged in the lower Colorado River of 3.3-5.2 $\mu g/g$ DW (Kepner and others, 1990). Livers from the lower Colorado River rails had a mean selenium concentration of 25.3 $\mu g/g$ DW, with values as high as 38.9 $\mu g/g$ DW. These selenium levels were similar to those found in water birds at Kesterson NWR, where significant reproductive failures have been documented (Ohlendorf, 1989).

Food-Chain Relations

Selenium cycling in aquatic ecosystems has been thoroughly discussed by Lemly and Smith (1987). As depicted in figure 8 in the "Development of Sampling Methodology" section of this report, dissolved selenium contributed by sources such as irrigation drainwater first is incorporated into lower trophic levels (plants and invertebrates). From there, the pathway can go directly into small forage fish and then birds, or biologically incorporated selenium can be deposited into sediment. Selenium that has accumulated in sediment then can be cycled back into the biota and remain at elevated levels for years after selenium input has ceased.

The most important selenium pathway in the Salton Sea includes accumulation by benthic invertebrates, particularly pileworms, and subsequent intake by detritus-feeding fish and fish-eating birds (fig. 37). It is apparent that as selenium is transferred through successive trophic levels in the food chain, selenium concentrations increase (that is, biomagnification occurs).

FIGURE 37 near here

The generalization that lower-trophic-level consumers have selenium concentrations that are 2 to 6 times higher than those of primary producers (Lemly and Smith, 1987) is valid for the Salton Sea (fig. 38). Selenium thresholds for water-bird food items (Heinz and others, 1987) are exceeded in the Salton Sea area only in larger forage fish and predatory fish (fig. 38). Thus, the larger piscivorous birds such as brown pelicans and double-crested cormorants are at greatest risk of adverse affects from selenium.

FIGURE 38 near here

Figure 37. Selenium pathway in the Salton Sea.

Figure 38. Selenium concentration in food-chain organisms of the Salton Sea.

In contrast to the Salton Sea, water in the rivers and drains is flowing, thus reducing the opportunity for a contaminated surface layer of sediment to develop. It is in this surface layer that bioaccumulation in plants and in benthic fauna generally occurs. Selenium is introduced into these habitats as a result of higher concentrations in water rather than in sediment. This conclusion is supported by selenium data from Setmire and others (1990) showing that selenium concentrations in sediment are lower in rivers and drains than in the Salton Sea, but that concentrations in water are higher in rivers and drains then in the sea. Biological selenium pathways in rivers and drains of the Imperial Valley are depicted in figure 39. In comparison with the selenium pathway in the Salton Sea, the main difference is lower bioaccumulation at the highest trophic levels. Large birds feeding in the rivers do not accumulate nearly as much selenium as those feeding in the Salton Sea. In the rivers and drains, selenium enters the food chain through water, and accumulation from sediments is much less than in the sea. Another factor is that birds such as great blue herons are opportunistic feeders; they forage in various habitats, including agricultural fields, where selenium may not be accumulating in the prey. On the other hand, piscivorous birds such as double-crested cormorants feed almost exclusively in the sea and entirely on fish that have elevated selenium concentrations.

FIGURE 39 here

Figure 39. Selenium pathway in rivers and drains.

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Selenium bioaccumulation in food-chain organisms for rivers and drains (fig. 40) shows an increase in concentration as trophic level increases. This trend is similar to that for the Salton Sea food chains, but with slightly lower values for similar trophic levels. Also, concentrations at the highest trophic level are only one-half those in the sea. For birds feeding in the rivers and drains, mean selenium concentrations for all trophic levels are at or below the possible-threat-to-survival threshold (fig. 40). However, the range of concentrations for some species, especially forage fish, extends well above the threat-to-survival threshold. Birds feeding on these fish in the rivers and drains could be exposed to concentrations that affect reproduction (7 $\mu g/g$ DW) and actual long-term survival (10 $\mu g/g$ DW) (Heinz and others, 1990).

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Figure 40. Selenium concentration in food-chain organisms of rivers and drains.

Boron

Results from past contaminant studies have shown that selenium is the only inorganic drainwater constituent that has been associated with abnormal development among water birds (Ohlendorf and others, 1986a; Hoffman and others, 1988). However, recent studies by Smith and Anders (1989) and Hoffman and others (1990a) demonstrated that dietary boron concentrations well below levels that occur in the environment represent potential adverse reproductive effects on waterfowl. In addition, evidence from other studies summarized in Eisler (1990) found that boron in both boric acid and borax forms produced mortality and teratogenicity during development when injected into bird eggs.

TABLE 17 ar here

Boron concentrations in biotic samples collected in the Salton Sea during 1988-90 as part of this study are summarized in table 17. Boron was found to bioaccumulate at most trophic levels; however, there was no indication of biomagnification through food chains. The data, on the contrary, reflect a biominification in both marine and freshwater food chains. This trend in boron bioaccumulation also is evident in data from Jenkins (1980), Schuler (1987), Schroeder and others (1988), Eisler (1990), and Lemly (1990). Boron concentration in biota, in a pattern similar to that in water (Setmire and others, 1990), generally was higher for the Salton Sea than for the rivers and drains (table 17). Limited sampling in areas not affected by agricultural drainwater, such as San Felipe and Salt Creeks, suggests that local sources of boron exist in the Salton Sea drainage.

Aquatic Vegetation

Algae.--Algae collected from the Salton Sea had the highest concentrations of boron found in any biological samples (table 17). No adverse effects on the algae itself are known to occur at concentrations (as high as 390 μg/g DW) detected in Salton Sea samples. In fact, boron concentrations of 11,000 μg/L in water of the Salton Sea (Setmire and others, 1990) are comparable to values found to be stimulatory to some marine algaes (Anita and Cheng, 1975). On the basis of data in Jenkins (1980), Salton Sea algae have boron concentrations as much as three times higher than those of marine algaes from areas not affected by contamination. Boron concentrations in filamentous green algae (table 18) from the Salton Sea are similar to those found at Stillwater WMA. The Salton Sea concentrations are somewhat lower than concentrations in algae from Kesterson NWR, and higher than concentrations at other drainwater-study reference sites.

TABLE 18 near here

Submerged vascular plants.--Submerged aquatic vascular vegetation was collected from Trifolium/Vail Drains only during the reconnaissance investigation (Setmire and others, 1990). As indicated in table 19, the boron concentration of the Salton Sea sample was within the range for other submerged aquatic vegetation collected from drainwater-contaminated areas such as Kesterson NWR, Stillwater WMA, and Carson Lake. The Salton Sea sample was 2.2 to 20.6 times higher in boron concentration than values reported in Jenkins (1980) for plants of the same genus (*Potomageton* sp.) in uncontaminated areas. Schuler (1987) found seeds of submerged aquatic vegetation to be considerably higher in boron than whole-plant concentrations and that boron concentrations also were higher in the winter months. The pondweed samples from Trifolium/Vail Drains were collected in December 1986 and (the seeds especially) may represent the highest level of boron encountered by wintering waterfowl feeding in the rivers and drains of the Salton Sea area.

TABLE 19 near here

Emergent vascular plants.--The highest boron concentrations found outside the sea were in cattails collected in San Felipe and Salt Creeks. This probably represents bioaccumulation from a natural source of boron unrelated to drainwater. These values are considered high in comparison with reported values (15.0-30.0 $\mu g/g$ DW, Adams and others, 1973). Substrate concentrations as low as 15 ppm (Maas, 1986) have been reported to be toxic to agricultural plants; however, tolerances of aquatic plants are not known.

Aquatic Invertebrates

Marine invertebrates.--Pileworms collected in the Salton Sea had the highest boron concentrations of sampled aquatic invertebrates (table 17). A composite sample of pileworms, amphipods, and waterboatmen (representing a typical water-bird diet) yielded a boron concentration of 20 µg/g DW, which is elevated in comparison with other food items analyzed but well below concentrations for pileworm composites. The waterboatman/amphipod composite had a similar value of 21 µg/g DW. A composite sample of only waterboatmen yielded a boron concentration less than the multiple-species composite and comparable to concentrations in waterboatmen collected from a drainwater-study reference (not affected by drainwater) site (Volta WMA; geometric mean 11.8, range 7.4-21 µg/g, DW) used for the Kesterson NWR wetland contaminant study done by Schuler (1987).

Freshwater invertebrates.--In an effort to determine potential bioconcentration of boron and other contaminants in invertebrates from river and drain sites, an in situ bioaccumulation bioassay was done. Asiatic river clams collected from the Colorado River and transplanted in the Trifolium drain and in the Alamo River showed a biominification of boron over time preceded by an initial increase in boron (fig. 41). The initial increase in boron concentration detected in early March was related to increased agricultural activity (thus, increased water use). As sediment loads and drainwater volumes stabilized during the growing season, boron concentrations in the transplanted clams decreased. Crayfish sampled from the river and drain sites had non-quantifiable levels of boron.

FIGURE 41 near here

Figure 41. Boron bioaccumulation in transplanted Asiatic river clams.

According to Eisler (1990) most invertebrates generally can tolerate boron in the water column at concentrations as high as 10 mg/L for extended periods without adverse effects. However, exposure to 13.6 mg/L of boron over a 21-day period has been shown to cause a reduction in number of broods, total young produced, mean brood size, and mean size in *Dapnia magna* (Gersich, 1984; Lewis and Valentine, 1981). Boron-in-water concentrations of this magnitude (as high as 11 mg/L) exist in the sea but not in the river and drain sites (Setmire and others, 1990).

Fish

Samples of forage fish from the river and drain sites (sailfin mollies and mosquitofish) and one species from the sea (longjaw mudsucker) had extremely high detection limits (as high as 45 µg/g DW); therefore, boron concentrations in all samples of these species were not detectable. However, substantial bioaccumulation at levels below these detection limits may occur. The detected boron level in mosquitofish (one composite; 25 µg/g DW) collected as part of the reconnaissance investigation in 1986 (Setmire and others, 1990) was similar to levels found at Kesterson NWR (16.9-25.9 µg/g DW) in 1985 (Hothem and Ohlendorf, 1989) and elevated in comparison with concentrations detected in the Stillwater WMA reconnaissance investigation (4.0-6.3 µg/g, DW; Hoffman and others, 1990b) and the San Joaquin River system (2.2 to 9.8 µg/g DW). Boron concentrations in bairdiella (geometric mean 6.2, range 5.0-8.3 µg/g DW) collected in this study were below levels found previously in bairdiella collected from the Salton Sea (Saiki, 1990). The reason(s) for this difference is unknown. Comparisons of boron concentrations in fish collected from the river and drain sites (Setmire and others, 1990) with those from the Salton Sea (Saiki, 1990; Setmire and others, 1990) show similar values, with slightly higher concentrations in foraging fish from the sea. M.K. Saiki (written commun., 1990) found that the orangemouth corvina had the lowest boron concentrations of fish inhabiting the sea. There are no known standards, criteria, or affect levels for boron in fish.

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Amphibians and Reptiles

Boron concentrations in samples of two species of herptofauna from the river and drain sites (bullfrog and spiny softshelled turtle) were low and at levels not known to cause adverse effects in these species (Eisler, 1990). Quantifiable concentrations of boron in prey species of frogs (waterboatman) and turtles (sailfin molly and mosquitofish; Setmire and others, 1990) were as much as five times greater than in the herptofauna, which indicates that biominification is occurring.

Birds

Migratory birds.--Boron concentrations in bird livers (fig. 42) were higher in waterfowl (northern shoveler and ruddy duck) than in shorebirds (coot, eared grebe, and white-faced ibis). Boron in bird muscle tissue was relatively low, with most samples being below detection limits (table 17). Birds utilizing the sea and mouths of rivers (marine and estuarine habitats) had higher levels of boron than birds feeding in the upper river, drains, and agricultural fields (freshwater habitats). Migratory waterfowl (female ruddy ducks) were sampled in November 1988 on arrival at the sea, 1 month later, and in March 1989 just prior to departure. As shown in table 20, levels of boron in liver samples were non-detectable on arrival and increased to quantifiable levels on departure from the sea. A simple linear regression was performed to show if the increase in boron concentration from autumn to spring was related to an increase in bird weight; the regression results showed that the relation between the weight of birds and boron concentration in liver was random ($r=0.03$, $F=0.869$, $P<0.360$).

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Ruddy ducks had the greatest range of boron concentrations in livers, and northern shovelers sampled throughout the winter of 1988 had the highest geometric mean. Ruddy ducks primarily eat pileworms, which are fairly high in boron, and shovelers feed on plants and planktonic invertebrates, which are fairly to extremely high in boron; thus, shovelers would be expected to have higher levels of boron than do ruddy ducks. These species of waterfowl also may incidentally consume algae, which harbors significant zooplankton biomass and has the highest boron concentrations found in biological samples of this investigation.

Figure 42. Boron concentration in livers of water birds and shorebirds from the Salton Sea area.

Boron concentration in food items of waterfowl at the Salton Sea ranged from 10 to 390 μg/g DW. Smith and Anders (1989) found reduced weight gain (in comparison with a control) in ducklings hatched from eggs laid by females fed diets containing as little as 35 μg/g DW of boron. When females in the same study were fed a diet of 388 mg/kg DW boron, duckling body weight, at hatch, from eggs laid by the female was significantly lower and duckling weight gain was reduced, in comparison with a control. Corresponding boron liver concentrations of these adult mallards were less than 3-4 mg/kg DW for birds fed 35 mg/kg DW and 7-24 mg/kg DW for birds fed 388 mg/kg DW. On the basis of this laboratory data and boron concentrations in waterfowl livers collected as part of this investigation, waterfowl at Salton Sea are ingesting a diet containing less than 388 μg/g DW boron, which agrees closely with the actual range of boron in food items (10-390 μg/g DW) from the sea. This range also indicates that growth rates in ducklings hatched from wintering waterfowl could be adversely affected. However, most waterfowl at the Salton Sea are migratory and nest elsewhere, making it difficult to determine if actual reductions in growth rate or body weight of ducklings is occurring as a result of feeding by adults in the Salton Sea area. As previously discussed, ruddy ducks sampled just prior to departure from the Salton Sea had boron concentrations in the liver that were elevated in comparison with to non-detectable levels when they first arrived. These elevated levels indicate that when these birds return to their breeding grounds, they have boron concentrations that potentially could cause sublethal adverse effects in ducklings.

Resident birds.--The only resident nesting species of bird that was examined extensively is the black-necked stilt. Carcass samples showed low levels of boron (table 17). Stilt food items consist of waterboatmen, amphipods, and pileworms, which have boron concentrations that ranged from 10 to 160 μg/g DW. As discussed in Smith and Anders (1989), a diet of 35 μg/g boron DW was found to cause a reduction in duckling weight gain. In the same study, corresponding boron concentrations in eggs of ducks fed 35 μg/g boron DW were 3-4 mg/kg DW. Boron concentrations found in stilt eggs in this investigation (fig. 43) were as much as two times greater than the quantitation limit. Figure 43 illustrates the cumulative distribution of boron in stilt eggs as it relates to levels found in eggs by Smith and Anders (1989).

FIGURE 43 near here

Figure 43. Cumulative distribution of boron in black-necked stilt eggs from the Salton Sea.

Growth rates of nestling stilts at Salton Sea were compared with those of stilts from a site not affected by agricultural drainwater (Bolsa Chica, Orange County, California) in 1988-89 (R.A. James, U.S. Fish and Wildlife Service, written commun., 1990). The comparison was made using bird weight in relation to tarsus length and wing length of young stilts. Tarsus and wing length are used to predict relative age. Shew and Collins (1990) have found wing lengths in black skimmers to be an accurate and dependable estimate of chick age. Coleman and Fraser (1990) found wing length of black and turkey vultures to be the best predictor of age of several variables examined. Analysis of covariance was used to investigate site differences with respect to the relation between weight and tarsus and wing lengths. The slopes of log(weight) in relation to log(tarsus) were significantly different ($100 \times r^2 = 97$, $F = 8.24$, $P = 0.0003$). Thus, the sites are significantly different in growth rates for juvenile black-necked stilts. After adjusting for the two covariants (tarsus and wing length), it seems that black-necked stilt young from the Salton Sea are significantly smaller (reduced growth rate) than young from the comparison sites. Although boron concentrations in stilt food items and eggs are comparable to values known to cause reduced growth in young birds, other variables may be fully or partially responsible for the reduced growth rates observed at Salton Sea. Grant (1982) extensively studied black-necked stilts at the sea and found that these birds have modified behaviors for the regulation and maintenance of egg temperatures at below-lethal levels, the prevention of overheating of adult birds on the nest, and the regulation of nest humidity. The effects of these modifications on juvenile stilt growth is unknown.

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Endangered birds.--A salvaged Yuma clapper rail (a Federally endangered species) from the southeastern part of the sea at Wister WMA had a whole-body boron concentration of 14.0 µg/g DW. The only other data for boron analysis on Yuma clapper rails, from birds collected on the Colorado River above the Imperial Dam (Radtke and others, 1988), had concentrations below detection limits (less than 5.0 µg/g DW) for whole-body analysis. An individual light-footed clapper rail collected from Seal Beach NWR in coastal Orange County, California, had a boron concentration of 34.4 µg/g DW (U.S. Fish and Wildlife Service, 1990b). No baseline or "normal" levels of boron are known for clapper rails; therefore, the significance of either of these values is unknown. However, on the basis of comparative levels for other bird species and the possible sensitivity of the endangered rail, boron is of concern to this endangered species.

Food-Chain Relations

Boron is incorporated into the food-chain base from water and sediment and bioaccumulates to the highest concentrations at the lower trophic levels (primary producers and primary consumers). Boron cycling examined in this investigation is illustrated in figures 44 and 45.

FIGURE 44&45 near here

In a pattern similar to that for Kesterson NWR (Schuler, 1987) and San Joaquin Valley (Lemly, 1990), aquatic vegetation and invertebrates typically accumulated boron to higher concentrations than found in surrounding water and sediments. Concentrations in aquatic invertebrates were lower than those in plants. Boron concentration in food-chain organisms in the Salton Sea and in river and drain sites is shown in figures 46 and 47, respectively. Appropriate reproductive thresholds (from Smith and Anders, 1989) are included in the figures.

FIGURE 46&47 near here

Organisms have been arranged in these figures according to relative trophic levels similar to those of Young (1984). This type of arrangement for trophic levels commonly is considered to be oversimplified. However, the Salton Sea is a relatively simple new, manmade system (Hagar and Garcia, 1988), in which most trophic relations are understood and not complex.

Figure 44. Boron pathway in the Salton Sea.

Figure 45. Boron pathway in rivers and drains.

Figure 46. Boron concentration in food-chain organisms of the Salton Sea, 1986-90.

Figure 47. Boron concentration in food-chain organisms of rivers and drains.

Invertebrates associated with sediments have higher boron concentrations than planktonic invertebrates. Boron concentrations in livers of birds (for example, ruddy duck) that feed on sediment-bound invertebrates where higher than whole-body concentrations for plankton-feeding birds (for example, black-necked stilts). Data from Wells and others (1988), Stephens and others (1988), and Klasing and Pilch (1988) show the same trend in boron concentrations for bottom-feeding fish in comparison with pelagic fish. Also, birds (such as shoveler) that feed on both vegetation and invertebrates had slightly elevated levels of boron in comparison with birds (such as ruddy duck) that feed mainly on invertebrates. However, all higher-trophic-level consumers that feed directly on lower-trophic-level organisms are bioconcentrating boron at levels known to have chronic reproductive effects on waterfowl (reduction of weight gain in ducklings and (or) reduced hatchling weight).

Migratory waterfowl had the highest boron concentrations of all types of birds sampled. Since these birds are highly mobile, not all sources of boron can be accounted for in this investigation. It has been documented, however, that these birds are arriving at the sea with moderately low levels (mostly nondetectable) of boron and depart with levels known to cause adverse reproductive effects. Although residential shorebirds, such as the black-necked stilt, may be bioaccumulating less boron than are waterfowl, accumulation of boron is sufficient to cause reduced weight gain in the young. Piscivorous birds feeding at the Salton sea also may be bioaccumulating boron at levels known to cause reproductive effects. Analysis of data for fish from the detailed investigation was limited, and more information is needed to determine the potential adverse effects on piscivorous birds such as the endangered California brown pelican and the double-crested cormorant. In summary, boron is rapidly removed through respiration and (or) excretion from progressively higher trophic levels in both marine and freshwater food chains of the Salton sea system. This biominification, however, does not prevent potential adverse reproductive effects on waterfowl and shorebirds that feed directly on lower-trophic-level food items.

Organochlorine Pesticides

Organochlorine pesticides (OC) were developed during the 1940's and 1950's to help increase food production through the control of pests. This was successfully achieved not only because of the toxicity of these pesticides but also because they were effective for a long period of time. However, because organochlorines are lipophilic and persistent, and were used extensively throughout the country, widespread bioaccumulation occurred in aquatic and terrestrial food chains. Long-lived species at the top of the food chain, such as bald eagles, were accumulating significant body burdens of OC's that caused serious reproductive problems.

The intensive agriculture within the Imperial and Coachella Valleys was no exception to the extensive use of organochlorine pesticides. Results of a California Toxic Substances Monitoring Program (TSMP) study of organochlorine bioaccumulation show that fish from the Imperial Valley show some of the highest body burdens in the State. Since 1978, total DDT and toxaphene in fish in the Imperial Valley routinely have exceeded the National Academy of Sciences (NAS) (1973) recommended levels for the protection of predators (total DDT, 1.0 mg/kg; toxaphene, 0.1 mg/kg WW) (TSMP, 1983a, 1983b). The latest TSMP data for 1989 show that toxaphene levels still are above the NAS threshold. Other organochlorines that have exceeded the NAS threshold in the Imperial Valley are endosulfan and dieldrin (threshold for endosulfan and dieldrin is 0.1 mg/kg).

DDT and Metabolites

DDT was introduced to the Salton Sea area as a low-cost broad-spectrum insecticide (technical DDT) and to a lesser extent as a component of dicofol products, an acaricide used heavily on cotton, formerly a major crop of the Imperial Valley. DDT was banned in the United States in 1972 (in Arizona in 1969), and in Mexico in 1983, and DDT has been regulated in dicofol during 1986-88 (now required to contain less than 0.1 percent DDT). However, recent concentrations of p,p'-DDE found in resident fauna in the Southwestern United States (including Texas, New Mexico, Arizona, and the Salton Sea area) are at levels associated with eggshell thinning and reduced reproductive success in birds (Clark and Krynitsky, 1983; Fleming and Cain, 1985; White and Krynitsky, 1986; Ellis and others, 1989; Ohlendorf and Marois, 1990). Clark and Krynitsky (1983) and White and others (1983) have suggested that recent use of DDT may have occurred in the southwest; however, Schmitt and others (1985, 1990) found no evidence of such use on the basis of fish data for the region. Aut Not ref.

Most recommended environmental concentrations and action levels for DDT are based on total DDT (DDT+DDE+DDD, including p,p' and o,p' homologs); reproductive thresholds and biological effects, on the contrary, have been correlated with p,p'-DDE. Total DDT concentrations are given in table 21 and p,p'-DDE concentrations are given in table 22 for all biota samples collected as part of the Salton Sea reconnaissance and detailed investigations. Results are similar to those for other recent studies throughout the United States: p,p'-DDE was found in the majority of the Salton Sea area samples (99 percent), p,p'-DDT was found in 33 percent, and p,p'-DDD was found in 32 percent of the samples. The o,p' homologs, which are derived from o,p'-DDT (an impurity of technical DDT), are less persistent than p,p' homologs and are not of significant concern.

TABLE 21 near here

TABLE 22 near here

Aquatic invertebrates

Aquatic invertebrates collected from the sea (waterboatmen and pileworms) had the lowest mean p,p'-DDE concentrations of all biota samples (table 21). Crayfish and clams collected from river and drain sites had mean concentrations approximately four and six times, respectively, greater than maximum mean concentration of Salton Sea invertebrates. DDT is highly toxic to some invertebrates and relatively nontoxic to others (U.S. Environmental Protection Agency, 1980a). On the basis of toxicity testing, the crayfish is the aquatic invertebrate most sensitive to DDT (U.S. Environmental Protection Agency, 1980a). However, crayfish collected as part of this investigation had relatively low p,p'-DDE levels, and no detectable p,p'-DDT was found.

Asiatic river clams had the highest DDE concentrations of all invertebrates. Because of their immobility and association with sediments, clams were an excellent bioindicator of DDE exposure. An elevated concentration (20 times greater than the geometric mean) was found in a composite clam sample collected from Vail Cutoff Drain. The high DDE concentrations probably are due to a high DDE sediment load. A composite clam sample from Wister Drain, which receives minimal amounts of drainwater, had no detectable concentrations of any DDT metabolites. Excluding these values, there were no large differences in concentrations from any other river and drain sites (range, 0.16-0.47 μg/g WW).

FIGURE 48 NEAR HERE

An in situ bioaccumulation study was initiated to determine if there was seasonal variation in DDE bioaccumulation and if DDT and its metabolites were being bioaccumulated in clams as a result of recent DDT use or from past use. The results of this bioassay are presented in figure 48. In a manner similar to that of boron, concentrations of DDE peaked in late winter/early spring when irrigation activities start to increase. During this period, the clams may have been exposed to increased DDT metabolites sorbed on soils and transported with tailwater runoff and (or) resuspension of sediments in drains (ditches) and rivers. Unlike many other contaminants, p,p'-DDE is highly persistent, and this persistence prevents rapid depuration of environmental concentrations. Pimental (1971) reported that eastern oysters containing about 151 ppm of DDT required approximately 3 months in clean water to lose 95 percent of their DDT burden. Other molluscs have been shown to lose as much as 75 percent of accumulated DDT after 15 days of flushing. Clams sampled from Trifolium Drain excreted 59 percent of their p,p'-DDE during 1 year. However, during that year, p,p'-DDT concentrations in the same clams increased by 40 percent. This increase in DDT represents a change in the proportional composition of the p,p' homologs. On the basis of these proportions, one possible explanation is recent use of DDT. These changes also may indicate that bioaccumulation of DDT and its metabolites in benthic invertebrates is a dynamic process that still is occurring in Imperial Valley years after any legal use.

Figure 48. DDT concentration in transplanted Asiatic river clams.

The DDE concentrations in transplanted clams from the Alamo River were higher than those from the Trifolium Drain. This same trend of higher river and lower drain concentrations in biota also was found in selenium and boron. The greater magnitude of sediment loads and drainwater inflow to the Alamo River in comparison with those of the Trifolium Drain may be responsible for the increased bioaccumulation of contaminants in aquatic invertebrates. These contaminants can be transferred to higher trophic levels in the food chains.

Fish

Freshwater fish.--The highest mean concentration (0.58 μg/g WW: mosquitofish) and highest overall concentration (5.7 μg/g WW; red shiner) of p,p'-DDE for whole-fish samples were from river and drain sites (table 21). Large bottom-feeding fish collected in the Imperial Valley as part of California's Toxic Substances Monitoring Program (TSMP) had levels of total DDT well above concentrations found in most forage and predatory fish collected as part of this investigation. The fish sampled for the TSMP represent larger and longer living fish species than those sampled during this investigation. According to a TSMP synopsis (1983a, 1983b), elevated levels of total DDT still existed in bottom-feeding fish found in the Alamo and New Rivers as of 1983. Channel catfish and common carp fillet samples from both these rivers represented some of the highest levels of DDT found as part of the statewide TSMP (written commun., 19__). DDT increased in concentration from 1978 to 1983, on the basis of both wet weight and lipid weight, for common carp in the Alamo River. Recent (1989) results show that total DDT concentrations in TSMP fish fillet samples from the Alamo and New Rivers were significantly lower than previous concentrations, indicating a downward trend for channel catfish and carp. All recent fillet samples collected from Imperial Valley as part of the TSMP had total DDT concentrations less than 1 μg/g (range 0.006-0.930 μg/g WW).

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The U.S. Fish and Wildlife Service's National Contaminant Biomonitoring Program (NCBP) reported that levels of DDT in fish in the upper Rio Grande and Colorado River systems (except for the Yuma, Arizona, station) were low (total DDT <0.05; p,p'-DDT <0.03 μg/g WW) and that levels at the Colorado River stations remained unchanged during 1976-84 (Schmitt and others, 1985, 1990). All river and drain fish samples from the Salton Sea study had total DDT values less than 0.05 μg/g, and 22 percent had p,p'-DDT greater than 0.03 μg/g WW. In 1984, higher DDE concentrations (greater than 1.0 μg/g WW) still were being found at the Yuma, Arizona, station (Schmitt and others, 1990). Elevated concentrations in migratory striped mullet at the Yuma station were believed to be caused by accumulation of DDT and metabolites when they frequent reaches of the Colorado River in Mexico, where DDT at that time still was used in agriculture (Schmitt and others, 1983, 1985).

TABLE 23 near here

DDE concentrations in mosquitofish from the river and drain sites are compared with other values for fish collected from the Salton Sea area, other drainwater locations, and nationwide in table 23. The mean DDE concentration of mosquitofish sampled as part of this study was 2.9 times greater than the 1980-81 NCBP mean average. Concentrations of p,p'-DDE in mosquitofish were higher than concentrations in mosquitofish from the Tulare Basin reported by Schroeder and others (1988). (Also, DDE concentrations in mosquitofish collected as part of the 1989 TSMP in Imperial Valley (Warren Drain) exceeded all concentrations reported in this study.) The maximum concentration for Tulare Basin mosquitofish was below the minimum concentration (0.54 μg/g WW) reported for mosquitofish in the Salton Sea area as part of this study.

Mosquitofish from contaminated sites have been shown to exhibit resistance to DDT toxicity (Vinson and others, 1963; Andreason, 1985). Although p,p'-DDE concentrations in mosquitofish in river and drain sites were elevated in comparison with data collected at other sites, concentrations were at levels not known to adversely affect the species directly.

Elevated DDE concentrations in red shiner from the Whitewater River, north of the Salton Sea, exceeded maximum concentrations found by the NCBP throughout the entire country in 1980-81 (2.57 μg/g, WW) and 1984 (4.74 μg/g, WW) (Schmitt and others, 1985, 1990). These results indicate the presence of elevated concentrations of DDT and its metabolites, presumably from past irrigated agricultural use, in the Coachella Valley.

Marine fish.--Mean concentrations of p,p'-DDE in tilapia from the Salton Sea (0.23 μg/g WW) were slightly higher than in tilapia composites from the lower Rio Grande River (0.16 μg/g WW; Wells and others, 1988). Mean DDE concentration in bairdiella (gulf croaker) was less than one-half that found in tilapia, and it was the lowest concentration found in any whole-fish sample. These values were slightly higher than values for bairdiella fillet samples collected from the Salton Sea as part of the 1989 TSMP (written commun., 19__). Because low concentrations were found in whole-body bairdiella samples, total DDT and (or) p,p'-DDE probably are not a concern for the health of adult bairdiella.

Total DDT concentration in the top aquatic predator of the Salton Sea, orangemouth corvina (fillet sample), was the lowest concentration found in any of the fish that were sampled (fig. 49). DDE concentrations in the corvina were comparable to 1989 TSMP bairdiella fillet samples (written commun., 19__). The orangemouth corvina is a long-lived high-trophic-level species that has a high potential for significant bioaccumulation of persistent contaminants such as DDE. The fact that DDE has not significantly bioaccumulated in corvina further indicates that DDT and its metabolites are not adversely affecting adult fish in the Salton Sea.

FIGURE 49 near here

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Although all three species of sportfish examined in this investigation (corvina, bairdiella, and sargo) had low levels of contamination, there is evidence that the ichthyoplankton stages of sportfish at the Salton Sea are especially sensitive to environmental contamination. All three species of sportfish sampled from the Salton Sea had malformation rates similar to those reported in areas containing known contaminants such as DDT (Matsui, 1989). Matsui (1989) concluded that some form of environmental contamination in the Salton Sea is causing the death of at least 6 to 11 percent of the developing eggs of the sportfish. Embryonic aberrations were significantly higher in earlier stages and represent the effect of environmental stress at a critical life stage (the period between cleavage and gastrulation). The types of malformations reported were not specific to a particular contaminant, but may represent synergistic effects of many contaminants, along with effects of temperature and salinity changes.

Figure 49. Total DDT concentration for three species of fish from the Salton Sea.

There has been some question as to whether recent use of DDT has occurred in Imperial Valley and (or) Mexico. Generally, 70 percent DDE, 20 percent DDD, and 10 percent DDT is the proportional composition of DDT found in fish in areas of historical DDT use (Schmitt and others, 1985). In 1984, the proportion of p,p'-DDE in NCBP fish samples had increased to 73 percent, indicating continued weathering of DDT and its metabolites (Schmitt and others, 1990). According to Menzie (1978), proportionately higher levels of p,p'-DDT indicate recent use of DDT in some form (technical DDT or as a component of dicofol). Disproportionately high levels of o,p'-DDT (an impurity and a less persistent form) also may represent recent inputs and (or) pollution sources other than pesticides (Schmitt and others, 1985). One tilapia sample collected from the Salton Sea had a somewhat disproportional composition of 67.4 percent DDE, 24.1 percent DDD, and 8.5 percent DDT, but all other samples were closer to accepted proportions for historical use of DDT. Uchida and others (1988), as cited in Schmitt and others (1990), found that tilapia metabolize DDT very slowly; thus, DDE proportions are expected to be lower for this species than for other species of fish. All the fish data from this investigation of the Salton Sea support the conclusion by Schmitt and others (1985, 1990) that DDE has not been used recently in the Southwestern United States.

Amphibians and reptiles

DDE concentrations in fat and eggs from softshelled turtles greatly exceeded levels found in bullfrogs (table 22). The higher concentration in turtles may be due to differences in food habits or in lipid content between the species. Little is known of the effects of DDT on amphibians and reptiles. Reptiles have been reported to be more sensitive to the effects of pesticides than are homeotherms. Reptile mortality has been observed at dose levels (as low as 0.01 g) that generally are safe for birds and mammals (Rudd and Genelly, 1956). DDT applications of 0.3-0.7 kg/ha to agricultural land have been shown to cause both sublethal and lethal effects on snakes, turtles, and lizards (Herald, 1949).

Residue concentrations found in Salton Sea softshelled turtles are within the range of a wide variety of values for reptiles reported in Hall (1980). Lipid-weight concentrations in fat were well above values for snapping turtle fat collected from contaminated marshes in New Jersey (0.16, 0.26, and 2.03 μg/g lipid weight; Albers and others, 1986), comparable to the value for a Hudson River snapping turtle (15 μg/g lipid weight), and well below the value for a Lake Ontario snapping turtle (87.6 μg/g lipid weight) as reported in Olafsson and others (1983).

Softshelled turtles are a high-trophic-level predator in the river and drains ecosystem, feeding primarily on crayfish, mosquitofish, sailfin mollies, and frogs. These food items had whole-body DDT concentrations about one-thirtieth to one-two thousandth the concentrations (WW) found in the turtle fat, indicating significant biomagnification. Increased metabolism of fat during certain times of the year may mobilize the DDT residues, making them more available to other tissues such as eggs and leading to possible sublethal or lethal effects. A DDE:DDT ratio of less than 10:1 in higher-trophic-level species is considered unusually low (Blus and others, 1987). Salton Sea turtle samples had no detectable DDT, indicating no current exposure to DDT. On the basis of this sparse data, DDE in turtles would be expected to decrease over time; however, current adverse effects of DDE on turtles in the Salton Sea area are unknown.

Birds

Migratory birds.--DDE concentrations in carcass and breast samples are important indicators of DDT exposure for individual birds. These tissues also are potential food items for birds of prey as well as other predators. Of the three migratory species of waterfowl collected, northern shoveler had the highest mean and maximum concentrations of DDE for breast samples (table 21). Eared grebe and ruddy duck samples had similar ranges (although grebes had a slightly higher mean concentration). As found at other trophic levels, the river and drain species (for example, shoveler) had higher levels than species that primarily utilize the Salton Sea.

Waterfowl DDE concentrations were comparable to those reported from carcasses of mallards (not detectable-1.4 ppm WW) and wood ducks (0.20-4.0 ppm WW) from the DDE-contaminated Yazoo NWR in Mississippi (White and others, 1988). Blus and others (1987) found nesting mallards in areas of low DDE:DDT ratios (less than 10:1; that is, areas of suspected recent DDT use) to have p,p'-DDE concentrations (breast muscle) with ranges of 0.09-0.21 and 0.02-0.63 μg/g WW. Canada geese from the same area had somewhat lower ranges of 0.06-.18 and 0.03-.38 μg/g WW. Although the DDE concentrations found in waterfowl tissue during this study were well above those reported by Blus and others (1987), the DDE:DDT ratios (greater than 56:1) were considerably greater than those reported in the recent past. Therefore, recent use of DDT is not evident and DDE levels are expected to decrease over time.

Current levels of DDT and its metabolites in sediment, water, and biota from the Imperial Valley still may pose a threat to migratory waterfowl utilizing the Salton Sea. Ohlendorf and Miller (1984) collected northern pintails throughout California and found the highest DDE concentrations at the Salton Sea. Mora and others (1987) collected pintails seasonally in California and Mexico and also found the highest concentrations at the Salton Sea. They also found that the highest concentrations were in winter birds, indicating accumulation on the wintering grounds. The detected levels were comparable to concentrations found in northern shovelers collected during this study.

Waterfowl of the Salton Sea area are ingesting a diet with DDE concentrations ranging from 0.01-5.7 $\mu g/g$, depending on individual food habits and on habitats utilized. A dietary intake of 2.8 to 3.0 mg/kg DDE (WW) has been shown to have adverse effects on reproduction of waterfowl (Heath and others, 1969; Longcore and Stendell, 1977). Waterfowl typically feed on plant material and (or) invertebrates that had DDE concentrations well above the 2.8 mg/kg reproductive threshold for waterfowl, although not all food items were analyzed. Any fish-eating waterfowl species (for example, grebes) may exceed not only the 2.8 mg/kg threshold, but also the NAS (National Academy of Sciences, 1973) guidelines for the protection of predators (based on whole fish) for freshwater species (1.0 mg/kg WW) or for saltwater species (0.05 mg/kg WW).

Liver and fat samples of white-faced ibis had some of the highest DDE concentrations for birds found in the Imperial Valley. This migratory species feeds mainly in the agricultural fields on terrestrial invertebrates that are in direct contact with sorbed DDE in the soils. Banding data for nesting ibis from Carson Lake, Nevada (Henny and Herron, 1989) indicate ibis band recoveries from several Mexico locations, including Mexicali, which is only 30-40 miles from where ibis were collected as part of this study (Brawley, California). Henny and Herron (1989) also reported that ibis in the Carson Lake area experience reproductive problems at DDE concentrations greater than 4 μg/g WW in eggs. Concentrations of greater than 4 μg/g cause a decrease in nesting success, and concentrations greater than 8 μg/g decrease brood size. Eggshell thickness is reduced by 23 percent at DDE concentrations of 8-16 μg/g and by 27 percent at concentrations greater than 16 μg/g (Henny and Herron, 1989).

On the basis of concentrations of DDE in food items from both the > nesting and wintering ground, ibis are not exposed to DDE in the Carson Lake area, likely are bioaccumulating DDE on the wintering grounds. Ibis liver and fat samples collected in the Imperial Valley had DDE concentrations (geometric mean: liver, 5.93 μg/g WW; fat, 5.57 μg/g WW) of the same magnitude as concentrations in ibis eggs collected at Carson Lake. DDE:DDT ratios of Carson Lake ibis eggs ranged from 6:1 to 86:1, and the highest p,p'-DDT concentration was 2.5 μg/g (WW). DDE:DDT ratios of Imperial Valley ibis fat samples ranged from 20:1 to 153:1, and the highest p,p'-DDT concentration was 0.54 μg/g WW. DDE concentrations in the food of the white-faced ibis wintering in Imperial Valley are not known. Food-item DDE concentrations need to be determined to better understand DDE exposure and bioaccumulation in this sensitive species.

Pelicans utilize the Salton Sea during all seasons of the year. The numbers of white pelicans are largest during spring and fall migration, and the numbers of California brown pelicans are largest (estimated to be 5,000 in 1990) during post-breeding dispersal and to a lesser extent in the winter (U.S. Fish and Wildlife Service, 1989). Auth Not nat White pelicans, which historically nested at the Salton Sea, now use the sea as a major resting area on their spring migration to the National Wildlife refuges of the Klamath Basin (Boellstorff and others, 1985). Elevated DDE concentrations in white pelican eggs collected from the Klamath Basin are believed to originate from wintering grounds farther to the south.

Anderson and others (1975) found that a dietary intake of 0.15 mg/kg total DDT (associated with 97 μg/g in pelican eggs) was unacceptably high for the endangered California brown pelican because of its correlation with below normal eggshell thickness and productivity. The increasing late summer population of California brown pelicans at Salton Sea feed mostly on corvina, tilapia, sargo, and bairdiella. A comparison of total DDT concentrations in fish collected as part of this investigation with dietary thresholds set for DDE, and with NAS guidelines for both freshwater and saltwater predators (1 μg/g WW), show that California brown pelicans utilizing the Salton Sea are consuming potentially high levels of DDT and its metabolites. These high levels may cause an increase of DDE in eggs, which is associated with below normal eggshell thickness and below normal productivity for this particular species.

Three birds of prey (osprey, and the endangered peregrine falcon and bald eagle) that uncommonly are found at the Salton Sea also are being exposed to unacceptably high concentrations of DDE in food items such as fish, shore-birds, and waterfowl. All three prey species historically have been known to have suffered population declines as a result of eggshell thinning and lowered productivity caused by excessive DDE accumulation.

The effects of DDE accumulation in birds on wintering grounds is difficult to relate to nesting success unless sources of DDE are not present at breeding locations. Such examples are Carson Lake white-faced ibis (Henny and Herron, 1989), Ruby Lake night herons (Henny and others, 1984. 1985; Henny and Blus, 1986), and Klamath Basin white pelicans (Boellstorf and others, 1985). In some instances birds may be exposed to high concentrations both on breeding grounds and on wintering grounds. For example, California brown pelicans that winter at the Salton Sea feed along the southern California Bight during the breeding season. Both of these areas have known continual high levels of DDT residues in fish. The preceding discussion shows that winter feeding areas for birds, such as the Salton Sea, can play a vital role in the reproductive success of migratory birds.

Resident birds.--DDE concentrations in carcass and muscle samples of resident birds were elevated in comparison with all other samples collected in this study. Black-necked stilts had the highest mean and maximum carcass and muscle concentrations of any resident bird for which more than 3 samples were collected. Other resident species were expected to have elevated DDE concentrations. These include piscivorous birds (double-crested cormorant, herring gull, great blue heron), other birds of prey (barn owl), or other species feeding in the fields (cattle egret). However, because birds were opportunistically collected, data for these species were inadequate to determine which feeding strategies resulted in the highest DDE concentrations.

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Resident bird DDE concentrations in muscle and carcass for the Salton Sea and for other contaminated areas are given in table 24. DDE concentrations in all Salton Sea resident birds were comparable to concentrations found by King (1989a) in resident olivaceous cormorants in a heavily contaminated location (Houston Shipping Channel) in Texas. However, mean and maximum DDE concentrations in Salton Sea cormorants were slightly higher than those reported for double-crested cormorants collected from the Houston Shipping Channel. Cormorants collected as part of the lower Colorado River reconnaissance investigation (Radtke and others, 1988) had a mean value 4 times greater than that found at Salton Sea, and 40 times greater than in fish species collected at the same location. King (1989a) found that DDE concentrations in olivaceous cormorant carcasses were 27 times greater than those in fish. Concentrations in cormorant samples from the Salton Sea were only 5 to 11 times greater than in fish samples (bairdiella, tilapia) from the Salton Sea. The reason for the differences in bioaccumulation factors is unknown at this time.

DDE concentration in a great blue heron muscle sample was 2 to 80 times greater than concentrations in fish species eaten by the heron. However, there are indications that the great blue heron is not sensitive to DDT (Fitzner and others, 1988). The DDE concentration of the heron was well within the range of values found in great blue heron hatchlings in the Northwestern United States (Fitzner and others, 1988). Those values were determined to be considerably below levels associated with mortality or reproductive problems in Ardeids (on the basis of studies by Ohlendorf and others, 1979, and Blus and others, 1980).

Egg collection for several species of birds of varying feeding strategies and habitats initially was planned for this investigation. Concentrations of DDE in eggs reflect levels in the female at the time the egg was laid and may influence reproductive success of birds (Ohlendorf and others, 1978). However, a recent decline in nesting success, specifically in piscivorous birds, prevented adequate sampling. Piscivorous bird nesting attempts and success have declined greatly at the Salton Sea in recent years (Salton Sea National Wildlife Refuge, written commun., 1990); for example, the black skimmer population has decreased an estimated 40 percent since 1987. In a study in south Texas, Custer and Mitchell (1987) found decreased hatching success to be correlated with DDE concentration, independent of eggshell thinning. Although the reason for this decline in black skimmer population is not yet understood, contaminants are suspected to have been a major factor.

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Table 25 summarizes data on active nests of colonial water-bird species traditionally monitored along the south end of Salton Sea as part of the refuge's annual colonial nesting bird survey.

Black-necked stilts were the only birds for which eggs were collected for DDE analyses. Concentrations of DDE were greater than two times those of American avocet eggs collected from highly contaminated Westfarmers evaporation ponds in southern San Joaquin Valley (Schroeder and others, 1988). The mean p,p'-DDE concentration for stilt eggs was greater than the 2.0 ppm DDE (WW) threshold associated with 10-percent eggshell thinning in osprey eggs (Wiemeyer and others, 1988) and slightly below the reproductive impairment threshold concentration (3.0 ppm WW for eggs) for brown pelican (Blus, 1982). Stilt-egg DDE concentrations and documented thresholds for other bird species are given in figure 50. Although these thresholds may not be completely appropriate to determine stilt reproductive thresholds, they provide a range to which the stilt egg concentrations can be compared. Actual eggshell thickness of 38 Salton Sea black-necked stilt eggs was found to be negatively correlated with DDE concentrations (fig. 51). However, no cracked or broken eggs were observed during the investigation (K. Voget and R.A. James, U.S. Fish and Wildlife Service, Oral commun., 1990).

FIGURE 50 near here

FIGURE 51 near here

Figure 50. DDE concentrations in black-necked stilt eggs and reproductive-impairment thresholds for various bird species.

Figure 51. Correlation between DDE concentration and eggshell thickness for black-necked stilts from the Salton Sea, 1988-89.

Ohlendorf and Marois (1990) found that the mean concentration of p,p'-DDE in eggs of black-crowned night herons collected at Salton Sea in 1985 exceeded the 8 μg/g WW reproductive success threshold for this species. The mean concentration was comparable to Lake Ontario (1972-73) night heron egg concentrations (11-12 μg/g; Price, 1977), which were associated with a reduced hatching success rate of only 36 to 39 percent. Also, Ohlendorf and Marois (1990), Henny and others (1984,1985), and Henny and Blus (1982) found that nightherons nesting at Ruby Lake, Nevada, were accumulating their high DDE concentrations while overwintering in southern California and Arizona. Great egret eggs collected as part of the Ruby Lake study had concentrations of 24.0 μg/g. In 1975, while legal use of DDT (as a component of dicofol in the United States and use as technical DDT in Mexico) and illegal use probably was still prevalent in Imperial Valley, snowy egret (feeding and nesting areas similar to those of great egrets) eggs collected from the Salton Sea had a mean concentration of 1.7 ppm WW and a range of 0.8-4.2 ppm WW (M.F. Platter, San Diego State University, written commun., 1976). In 1976, pesticide residues were suspected of causing reproductive problems, including an increased egg mortality at Salton Sea colonial nesting rookeries (M.F. Platter, written commun., 1976). Eggshell thinning for snowy egret and cattle egret was 18.8 and 17.3 percent, respectively, in comparison with pre-1953 museum eggs. DDE concentrations in snowy egret eggs (WW and lipid weight) correlated well with decrease in eggshell thickness. Platter (written commun., 1976) stated that it was unlikely that adult mortality was occurring at the Salton Sea. On the basis of historical and present DDE bird residues, however, it is highly probable that DDE levels resulting from historical use in the Imperial Valley still may be causing reproductive impairment in resident birds.

An attempt was made to correlate DDE bioaccumulation and nesting location of black-necked stilts. Mean concentrations for different nesting populations of black-necked stilt are given in figures 52 and 53. Some of the variation in mean values may be due to small sample sizes, but it is apparent that the RH, Hazard, and Reidman Pond populations have elevated levels of DDE (that may reflect increased DDE loadings) in comparison with the other locations.

FIGURE 52&53 near here

Resident birds of the Salton Sea are ingesting food items with DDE concentrations ranging from 0.01 to 14.8 ppm WW. Birds such as waterfowl and shorebird species that feed on invertebrates are ingesting DDE concentrations ranging from 0.10 to 0.68 ppm WW. Piscivorous birds are ingesting higher DDE concentrations of 0.10 to 5.7 μg/g WW, and other birds of prey are ingesting still higher concentrations of 0.10 to 14.8 μg/g WW. White and others (1984) found elevated concentrations of DDE (0.8-2.5 μg/g WW) in black skimmer eggs with no apparent adverse effect in areas where fish DDE residues were 0.1-1.5 ppm. Thus, in a pattern similar to that for migratory waterfowl, resident piscivorous birds and birds of prey, on the basis of published thresholds and guidelines, are at the greatest risk of DDE contamination within the Imperial Valley.

Figure 52. p,p'-DDE concentration in black-necked stilt eggs.

Figure 53. DDE concentration in black-necked stilt eggs from selected nesting populations in the Salton Sea area, 1989.

Resident shorebirds such as the black-necked stilt show elevated concentrations of DDE in carcass and eggs with an apparently small dietary intake of only 0.01 to 0.08 μg/g WW. The resultant bioaccumulation factor in body tissues is as great as 1,200 times. There is concern that if stilts are adversely affected by DDE even though DDE levels in their food were low, more environmentally sensitive species such as the endangered Yuma clapper rail may also be effected. Declines in colonial water-bird populations, on the basis of thresholds and guidelines established for piscivorous birds, may be related to elevated DDE concentrations and other drainwater contaminants. Gulls and mammals (such as the raccoon) that eat bird eggs and fish also are being exposed to some of the highest DDE concentrations found in the Imperial Valley. Typically, aquatic species are more sensitive to DDE contamination (National Academy of Sciences, 1973). However; there is evidence that birds feeding primarily in the agricultural fields also are accumulating elevated levels of DDE. Resident birds of concern are white-faced ibis, cattle egret, and several species of birds of prey.

Food-chain relations

Although DDT is not a contaminant originating directly from irrigation drainwater, DDT and its metabolites (DDE and DDD) are mobilized by tailwater runoff or by resuspension of sediment in the drains and rivers. The low water solubility and high lipophilicity of DDT have resulted in bioaccumulation of DDT and its metabolites in fish and wildlife species throughout the United States (U.S. Environmental Protection Agency, 1980a). Lower-food-chain organisms had the lowest concentrations and higher-food-chain organisms had the highest concentrations of p,p'-DDE and total DDT. This trend of increasing DDE through the food chains has been documented in several studies, including Hickey and Anderson (1968) and King (1989a,1989b). DDE concentration/food-chain relations for the Salton Sea and for its associated river and drain systems is illustrated in figures 54 and 55, respectively. As shown for selenium, the more complex and longer the food chains are , the more likely it is that the toxic effects of DDE will be seen in higher-trophic-level species. Species associated with river and drain habitats (freshwater) typically had higher concentrations of p,p'-DDE and total DDT than similar species associated with the Salton Sea (estuarine and marine). The river and drain species were in closer contact with the main source of DDT--the agricultural fields (through tailwater runoff and resuspended sediments). Also, birds that feed in the fields (white-faced ibis and cattle egret) had some of the highest levels of DDE found during the study.

FIGURES 54-55 near here

Figure 54. DDE pathway in the Salton Sea.

Figure 55. DDE pathway in rivers and drains.

River and drain (freshwater) species had higher concentrations of total DDT and p,p'-DDE than Salton Sea (estuarine/marine) species; on the basis of reproductive thresholds and NAS guidelines, however, both groups may be adversely affected as a result of their dietary intake of total DDT. Total DDT and p,p'-DDE concentrations for food items sampled in the river and drains and in the Salton Sea, with appropriate biological-effect thresholds for each

FIGURE 56-59 near here

system, are shown in figures 56-59. On the basis of these data, predatory birds in the Imperial Valley are at the greatest risk of DDT contamination. Within this group, piscivorous and egg-eating birds had some of the highest total DDT and p,p'-DDE body-burden concentrations. Also of concern are birds feeding in the agricultural fields, but unless DDE levels in food items for these species are known, it is not possible to determine the full impact of irrigation runoff. Prey items of these birds, such as earthworms, reflect the dosage of DDT in soil and are known to accumulate high concentrations of organochlorine insecticides (Byers and Krynitsky, 1989).

Figure 56. Total DDT concentration in food-chain organisms of the Salton Sea.

Figure 57. p,p'-DDE concentration in food-chain organisms of the Salton Sea.

Figure 58. Total DDT concentration in food-chain organisms of rivers and drains.

Figure 59. p,p′-DDE concentration in food-chain organisms of rivers and drains.

Although resident bird species typically had higher concentrations than migratory species, both species may be experiencing reproductive impairment as a result of DDE contamination from Imperial Valley. According to Henny and Herron (1989) and Boellstorff and others (1985), migratory species with no or little DDE exposure on the breeding grounds are experiencing elevated DDE concentrations and, in some cases, documented reproductive impairment as a result of wintering-ground accumulation of DDE. A north-south organochlorine contaminant gradient (increase from N to S) in migratory waterfowl has been observed by Ohlendorf and Miller (1984) and Mora and others (1987), along with an apparent reverse pattern farther south in other wintering grounds in Mexico. Resident and migratory Salton Sea species are exposed to the highest concentrations of DDE, on the basis of the clam bioaccumulation study, during late winter/early spring because of the increased agricultural activities during that time. Mora and others (1987) also found that DDE concentrations in pintails at the Salton Sea were higher in late winter (February-March) as opposed to early winter (December-January). The late-winter period represents greater tailwater runoff and resuspended sediments associated with increased irrigation, including preplant leaching of soils. This also is the time when large concentrations of resident and migrating birds are present in the Imperial Valley and, specifically, the Salton Sea. Resident and migratory species begin nesting soon after having been exposed to these high concentrations of DDE.

The Salton Sea and Imperial Valley area has the highest DDE concentrations recorded in fish (Toxic Substances Monitoring Program, 1983a, 1983b) and birds (Mora and others, 1987; Ohlendorf and Miller, 1984; Ohlendorf and Marois, 1990) in the State of California. Previous studies at the Salton Sea (Ohlendorf and Marois, 1990; Toxic Substances Monitoring Program, 1983a, 1983b; Matsui, 1989) have shown that DDE concentrations were at levels that have been associated with reproductive impairment in birds and, possibly, abnormal development in young fish. Fish species of both the river and drain and sea locations had relatively low concentrations of DDE; however, residue concentrations of DDE (or some other contaminant) in the eggs of mature fish may be lethal to the developing fry. Other high-trophic-level species, such as the softshelled turtle, had extremely high levels of DDE in fat and eggs, but the significance of this is not known. In general, reptiles are less sensitive to orgaonchlorine contamination than are fish (Hall, 1980).

Ultimately, birds are at the greatest risk of DDE contamination at the Salton Sea and the rivers and drains. In general, species affected by eggshell thinning feed mainly at the top of a food chain on birds and (or) fish (Hickey and Anderson, 1968). Significant species differences exist in the effects of DDT and its metabolites on avian reproductive success as a result of complex interactions involving different ecological relations and physiological mechanisms (Risebrough and others, 1970; Stickel and Rhodes, 1970). Yet, in this investigation, the data are indicative of potential reproductive impairment of birds of several ecological niches, including shorebirds, piscivorous birds, and birds of prey. In the Imperial and Coachella Valleys, numerous resources under Department of the Interior trusteeship are at risk, including several species with known sensitivities to DDE bioaccumulation; these include three endangered species--peregrine falcon, California brown pelican, and bald eagle--as well as osprey and herring gull.

DDE concentrations in biota of the Salton Sea area are among the highest known for California, and in some cases they are higher than national biomonitoring results. However, on the basis of DDE/DDT ratios and DDT/DDE/DDD proportions, there is little evidence of recent DDT use. It has been suggested that continued elevated DDE residues generally may be attributed to dicofol use (Hunt and others, 1986). It is believed that elevated DDE concentrations in biota in the Salton Sea area are a result of past heavy use of technical DDT, in addition to use in Mexico through the 1970's and early 1980's and extensive use of dicofol through the 1980's.

Other Organochlorine Pesticides

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A total of 24 organochlorine pesticides (not including DDT and its metabolites) and their metabolites were analyzed in a variety of species from the Imperial Valley (table 26). Results that show 18 (75 percent) of 24 organochlorine compounds were found above detection limits in at least one sample. Of these, only two, toxaphene and hexachlorobenzene, were detected at concentrations greater than 1 mg/kg (ppm). The most frequently detected organochlorine pesticides were dieldrin in 60 percent of samples, and DCPA (dacthal®), in 54 percent. Other compounds detected at concentrations greater than 0.1 mg/kg include oxychlordane, trans-nonachlor, and beta benzene hexachloride. However, none of these organochlorines were found in fish above the National Academy of Sciences (NAS) threshold of 0.1 mg/kg to protect predators (National Academy of Sciences, 1973).

Toxaphene, a broad-spectrum insecticide, was one of the most heavily used agricultural chemicals on a global scale. It is extremely persistent in soil and water, with documented half-lives as great as 11 years (Eisler and Jacknow, 1985). The highest concentration of toxaphene, 7.0 mg/kg, was from a composite of Asiatic clams collected from the Vail cutoff drain, which receives considerable subsurface drainwater flow. The only other toxaphene detected in clams was 1.1 mg/kg WW at Johnson drain in the Coachella Valley. Because Asiatic clams are nonmobile and benthic, they serve as good bioindicators of pesticide input to their environment.

Spiny softshelled turtles taken from the Vail drain and from Hazard unit of the Salton Sea NWR had accumulated toxaphene concentrations in fat as high as 6.2 mg/kg WW. These results indicate that toxaphene usage has been high in agricultural areas in the Vail drainage system. Toxaphene was banned for any use beyond 1986 (U.S. Environmental Protection Agency, 1982) in the United States; therefore, the documented concentrations in biota are being accumulated from past uses.

All six turtles had significant concentrations of toxaphene (greater than 2.3 mg/kg) in their fat, and one female had 1.0 mg/kg in her eggs. These values are higher than those reported by Hall (1980) for softshelled turtles but considerably lower than the 154 mg/kg DW found in painted turtles killed by toxaphene (Finely, 1960). Autho Not ref

Toxaphene, like many other organochlorine pesticides, tends to accumulate in fat and may be safely stored by reptiles in the relatively isolated fat bodies (Hall, 1980). However, during periods of increased fat metabolism, such as reproduction, contaminants may be mobilized to other tissues such as eggs or, more critically, to the brain. D.

Toxaphene also was found in black-necked stilt eggs and ranged from less than the detection limit (0.01 mg/kg) to 1.0 mg/kg. Toxaphene has been shown to produce severe embryotoxic effects, including dislocated joints and poor growth in mallard ducklings, when used at application rates in excess of 1.12 kg/ha (Hoffman and Eastin, 1982). As previously mentioned, no gross abnormalities were found in black-necked stilt chicks; however, growth for Salton Sea birds was slower than for birds from coastal nonagricultural areas.

Hexachlorobenzene (HCB) residues have become widespread throughout the environment (Zell and Ballschmiter, 1980) because of its extensive use as a fungicide and because it is a byproduct of the production of other chlorinated hydrocarbons (Villanueva and others, 1974). In spite of the fact that commercial production of HCB in the United States was discontinued in 1976, waste byproducts continue to represent a significant source (U.S. Environmental Protection Agency, 1980b).

In the Imperial Valley, HCB has been detected in fish at concentrations near the 0.1 µg/g NAS-recommended threshold to protect predators (McCleneghan and others, 1981) and in pintails wintering at Salton Sea (Ohlendorf and Miller, 1984; and Mora and others, 1987). However, the HCB concentrations found in this study in white-faced ibis, 0.7 mg/kg in liver and 1.1 mg/kg in muscle, and in a barn owl, 1.3 mg/kg, are considerably higher than any other reported HCB concentrations from the Salton Sea area. These concentrations may be high enough to cause reproductive effects such as delayed egg production that have been documented in chickens (Hansen and others, 1978). However, it is not known how much HCB has been contributed to the Imperial Valley either as a result of agricultural activities, including irrigation and drainage practices, or contamination from other sources such as industrial waste byproducts.

Dieldrin historically has been used in agriculture--mostly for control of pests on corn and citrus crops; currently, in the United States, it is used only for subsurface soil injection to control termites (U.S. Environmental Protection Agency, 1980c). Even though dieldrin and aldrin (the source of most environmental dieldrin residue) have not been used in the Imperial Valley as pesticides since 1975, more than 60 percent of all biological samples collected for this study had detectable quantities of dieldrin (table 25). This high rate of detection is attributable, in part, to the fact that dieldrin is the most stable member of the chlorinated cyclodiene insecticides (Matsumura and Bousch, 1967) and, therefore, is very persistent in the environment. The National Contaminant Biomonitoring Program (Schmitt and others, 1990) has not documented any appreciable changes in dieldrin concentrations in fish from the Great Lakes and major rivers of the midwest from 1978-79 to 1984. This consistency suggests that dieldrin residues remaining in agricultural soil can be a threat to fish and wildlife for some time to come.

In spite of the persistence of dieldrin and the high rate of detection, no fish collected from this study were above the 0.1 μg/g NAS threshold for the protection of predators. However, recent results from the TSMP showed that mosquitofish from the Warren drain of the Imperial Valley had dieldrin concentrations (0.14 μg/g WW) above this threshold ( ). A more comprehensive contaminant survey might show that fish from other locations in the Salton Sea area also have concentrations that exceed the NAS threshold.

Other prey items, such as pileworms, waterboatmen, and frogs, had either nondetectable or very low dieldrin concentrations. In contrast, fat from spiny softshelled turtles had the highest concentrations, as high as 0.85 µg/g WW, from this study. Because dieldrin is nonpolar, it is lipophylic and tends to partition in fatty tissue at higher concentrations (Heath and Vandekar, 1964). However, even the highest observed concentration was well below values associated with residue found in turtles killed after field applications (Hall, 1980).

Generally, dieldrin was low (less than 0.1 µg/g WW) in birds except for black-necked stilts, white-faced ibis, and great blue heron. The highest observed concentration of 0.33 µg/g WW was found in a black-necked stilt. Dieldrin concentrations from northern shovelers (nondectable to 0.02 µg/g WW) and ruddy ducks (nondetectable to 0.02 µg/g WW) were comparable to waterfowl sampled in 1981-82 from the Imperial Valley by Ohlendorf and Miller (1984) and Mora and others (1987). Pintails sampled from the Salton Sea in October and November by Ohlendorf and Miller (1984) had no detectable dieldrin, but samples collected in December and January had concentrations of 0.02 and 0.06 µg/g WW for males and females, respectively. This increase suggests that waterfowl are accumulating dieldrin while wintering at the Salton Sea.

White-faced ibis, which feed in agricultural fields, had detectable dieldrin in all 18 samples collected, with concentrations ranging from 0.02 to 0.22 µg/g WW. This 100-percent detection rate probably reflects the fact that dieldrin is very persistent in the soil at the point of its application where it can be transferred to earthworms and other soil invertebrates fed on by the ibis.

The only bird eggs sampled from the Imperial Valley were from black-necked stilts. These mostly resident birds must be accumulating dieldrin locally because 80 percent of the 122 eggs analyzed had detectable residue, with concentrations as high as 0.15 $\mu g/g$ WW. It is not known what possible effect these residues may have; however, dieldrin has not been shown to cause eggshell thinning in either mallards or coturnix (Haegele and Tucker, 1971). Auth No. ret

In spite of the persistence of dieldrin in the soils of the Imperial Valley, residues observed in this study indicate that food items are below values known to cause harm in birds. Residues from the birds also are below levels known to have detrimental effects (Stickel and others, 1969).

Assessment of Resource Susceptibility to Contaminant Effects

On the basis of data from this study and the reconnaissance investigation, as well as from previous studies, 93 species of resident or regular-migrant birds in the Salton Sea area potentially are adversely affected by contaminants related to irrigation drainwater. This number represents 57 percent of the 164 regular-migrant and resident bird species of the Salton Sea. The other 43 percent represents species for which adequate data were not available to determine presence or absence of potential contaminant effects. In addition, this list does not include more than 200 rare, erratic, and accidental species found at the Salton Sea, such as roseate spoonbill, magnificent frigatebird, sooty shearwater, and booby species, which also might have significant exposure to contaminants related to irrigation activities in the Salton Sea area.

TABLE 27 near here

Drainwater contaminants of concern and other relevant information for each of the 93 species of birds identified as being subject to potential adverse effects related to drainwater contaminants are summarized in table 27. The status, feeding habitat, numbers, and food-item data were compiled from U.S. Fish and Wildlife Service (1987), Dritschilo and others (1983), and Salton Sea NWR staff (oral and written commun., 1990). Determination of contaminant of concern and degree of concern were assigned on the basis of concentrations of contaminants in food items, documented thresholds, status, feeding habitat, composition of diet, and (or) documented sensitivities to particular contaminants.

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A summary of the number of species (by category) that potentially are adversely affected by selenium, boron, or DDE is given in table 28. Overall selenium is of concern for the greatest number of species and DDE is of most concern for endangered species. Selenium effects primarily are aquatic based, and higher-trophic-level species are of the greatest concern for selenium; terrestrial-feeding birds of prey such as red-tailed hawk and prairie falcon are of little or no concern. Boron-contamination concerns rest primarily with migratory waterfowl and shorebirds, including a few birds of prey, piscivorous birds, and many terrestrial feeders. Most migratory waterfowl and shorebirds (mainly sandpipers) are of little concern with respect to DDE. In summary, the groups at greatest risk are (1) the piscivorous birds, for which levels of concern are high for selenium, primarily in the Salton Sea, and for DDE, both in the Salton Sea and river and drain locations; (2) shorebirds, which feed mainly on aquatic invertebrates and for which levels of concern are variable for selenium and boron in both the Salton Sea and river and drain locations, and for DDE in the river and drain locations; (3) waterfowl, for which levels of concern are high for selenium and boron in both the Salton Sea and river and drain locations; and (4) terrestrial-feeding birds for which levels of concern are high for DDE.

SUMMARY AND CONCLUSIONS

The factors controlling contaminant concentrations in subsurface drainwater are soil characteristics, hydrology, and agricultural practices. Although there is no apparent spatial pattern to the distribution of specific conductance or of dissolved-solids, selenium, or boron concentrations in the Imperial Valley, higher concentrations commonly are associated with clayey soils. Low infiltration rates in these soils result in increased evaporation and, thus, evaporative concentration. These areas of high concentration generally are near the Salton Sea, the major topographic depression in the area, although high concentrations also occur in other areas throughout the Imperial Valley. Mesquite Lake, one of these areas of high concentration, is a localized topographic depression near the city of El Centro.

Regression of hydrogen and oxygen stable-isotope ratios in samples collected from sumps demonstrates that Colorado River water is the sole source of subsurface drainwater in the Imperial Valley. These data also indicate that evaporation is the main process controlling dissolved-solids concentration in subsurface drainwater. The $100 \times r^2$ value for this relation is significant at 96, with an α value of less than 0.01. Further regression analysis shows that chloride and boron, as well as selenium, in subsurface drainwater also can be attributed to evaporative concentration of Colorado River water.

Elemental ratios of selenium to chloride demonstrate that selenium detected in subsurface drainwater throughout the Imperial Valley originates from the Colorado River. The median 1,000 × Se/Cl ratio for subsurface drainwater is similar to that of Colorado River water in the East Highline Canal. Variations in the Se/Cl ratio provide indications of either sources or sinks of selenium. In the area bordering the southern end of the Salton Sea, these ratios are significantly lower than in other parts of the Imperial Valley. These lower Se/Cl ratios indicate that selenium is being removed from the water and likely adsorbed to the sediments. This process occurs under reducing conditions, which are present along the southern border of the Salton Sea. Coupled with the presence of reducing conditions, high chloride from the Salton Sea may also influence subsurface drainwater, thus affecting the Se/Cl ratios. The Salton Sea is an excellent example of a selenium sink. The Se/Cl ratio in the Salton Sea is several orders of magnitude lower than the Se/Cl ratio in the fields of the Imperial Valley. Selenium in the inflowing water to the Salton Sea is selectively removed. One possible mechanism of removal, on the basis of published findings from laboratory studies and field studies in other areas, is that selenate-respiring bacteria concentrate elemental selenium in the bottom sediments where it is available to the benthic biota. No apparent spatial pattern was discerned in the distribution of selenium in the bottom sediments of the Salton Sea.

Ground-water samples collected from multiple-depth wells and lysimeters at three sites (northern, middle, and southern) in the Imperial Valley indicated that depth of infiltration and amount of evaporative concentration varied according to soil type. Analysis of tritium concentrations in these shallow wells and lysimeters indicated that clayey soils, in comparison with sandy soils, significantly retarded the movement of irrigation water through the soil profile. Water at depth in these clayey fields had elevated dissolved-solids concentrations.

Selenium loading to the Salton Sea, calculated using the median selenium concentrations in subsurface drainwater and in the Alamo River at the outlet, indicates that about 60 percent of the discharge to the Salton Sea is water of very low selenium and dissolved-solids concentrations (using Colorado River water as a diluent), and 40 percent of the discharge is higher selenium drainwater. The low selenium and dissolved-solids water consists of tailwater runoff, canal seepage, and underground flow of canal water. These same calculations demonstrate that about 15 percent of the selenium and boron is lost (relative to chloride) to the river sediments. The selenium load discharged to the Salton Sea from the Alamo River is about 6.5 tons/yr. For boron, the load discharged by the Alamo River is about 460 tons/yr. Calculations were not made of the New River ratios for the large volume of water entering the United States from Mexico.

Time-series study of selenium concentration in subsurface drainwater indicated that concentration generally varied directly with volume of flow from the sump. For the entire data set, selenium concentrations in May 1986 were similar to selenium concentrations in May 1988, $100 \times r^2 = 78.5$ with an α value less than 0.01 and a slope near 1.0. Subsurface-drainwater concentrations that were high in 1986 also were high in 1988, and those that were low remained low.

Drainwater contaminants, including selenium, boron, and DDE, were determined to bioaccumulate in migratory and resident birds utilizing the Imperial Valley. These contaminants are incorporated in bird tissues through the consumption of food. On the basis of in situ clam bioaccumulation assays, levels of selenium, boron, and DDE fluctuated seasonally. Temporal variation in boron concentration also occurred in ruddy ducks collected at three intervals during the wintering period at the Salton Sea. In both cases, elevated contaminant levels correlated with increased drainwater inflow during late winter and early spring agricultural activities.

Synergistic effects of these contaminants in birds were not evaluated. Possible interactions of selenium and boron with other contaminants may occur, as suggested by Lemly (1990). On the basis of results of this investigation, it cannot be determined if these contaminants may have synergistically or antagonistically interacted in birds from the Imperial Valley.

Selenium is bioaccumulating in both marine and freshwater food chains within the Imperial Valley A distinct correlation between higher selenium concentrations and higher trophic levels was observed. Also, the marine food chain was higher in selenium, at comparable trophic levels, than the freshwater food chain. This increased marine bioaccumulation puts piscivorous birds feeding in the Salton Sea at the greatest risk of selenium toxicity. A resident piscivorous bird (double-crested cormorant) had the highest liver selenium concentrations of marine birds collected during the study.

Waterfowl that feed on food items containing more than 4 $\mu g/g$ DW of selenium also are at risk. Northern shovelers had the highest liver selenium concentrations of freshwater species collected. These levels accumulated while the birds wintered in the Imperial Valley. Comparable historical data show that an increasing selenium burden in northern shovelers is occurring over time.

Black-necked stilts, resident shorebirds within the Imperial Valley, were exposed to levels of selenium that were sufficient to cause embryotoxicity in 5 percent of the eggs. The highest concentration of 35 $\mu g/g$ DW is comparable to mean selenium concentrations in stilt eggs at Kesterson NWR.

Body burdens in the endangered Yuma clapper rail show an exposure to selenium that may be affecting reproduction. Similar body burdens and potential adverse effects have been documented for rails from the Lower Colorado River.

Temporal data show no statistically significant increases in selenium burdens in ruddy ducks wintering at the Salton Sea. However, it is probable that selenium burdens are quickly established (in about 1 week) as birds arrive at the Salton Sea in the autumn and are maintained at an elevated level until the birds leave in the spring.

Selenium was bioaccumulated by "clean" Asiatic river clams placed in a major irrigation drain (Trifolium Drain) after increased irrigation during spring planting. Indigenous clams accumulated selenium in proportion to the relative irrigation drainwater inflow, thus showing that clams can serve as excellent selenium biomonitors.

The only possible documented adverse effect on fisheries was the exposure of some mosquitofish to sufficient selenium within the Trifolium Drain to cause body burdens to exceed the 12 µg/g DW reproductive threshold, Boron was found to bioaccumulate at most trophic levels in marine and freshwater systems of the Salton Sea. Boron concentrations in biota generally were higher at the Salton Sea in comparison with river and drain samples. Limited sampling in areas not affected by agricultural drainwater indicate that minor local boron sources exist in the Salton Sea drainage. Aquatic vegetation and invertebrates of the Salton Sea and river and drain sites had the greatest concentrations of boron in this investigation. Invertebrates associated with sediments had higher levels than planktonic invertebrates. Migratory waterfowl feeding directly on food items containing boron concentrations as low as 35 $\mu g/g$, on the basis of laboratory studies, may be experiencing chronic reproductive effects such as reduction of weight gain in ducklings and (or) reduced hatchling weight.

Resident shorebirds (black-necked stilts) are bioaccumulating less boron than migratory waterfowl; however, there is adequate accumulation to cause reduced weight gain in the young. Growth rates of black-necked stilt young at the Salton Sea in 1989 were significantly lower than growth rates of stilts from sites (at Bolsa Chica) not affected by agricultural drainwater.

Although organochlorine pesticides do not originate directly from irrigation drainwater, they are continuing to be mobilized by tailwater runoff and (or) by resuspension of sediment in the rivers and drains flowing into the Salton Sea. Elevated concentrations of DDE (DDT metabolite), toxaphene, and dieldrin were found mainly in higher-trophic-level species such as softshelled turtle, piscivorous birds, and birds of prey.

DDE was found in 99 percent of all analyzed samples. Lower-food-chain organisms had the lowest concentrations and higher-food-chain organisms had the highest concentrations of p,p-DDE and total DDT. Species associated with freshwater (rivers and drains) had higher concentrations than species collected from the Salton Sea. Some of the highest concentrations were found in birds feeding in agricultural fields on invertebrates and (or) small mammals.

Migratory and resident species of birds may be experiencing reproductive impairment as a result of DDE contamination in Imperial Valley. Migratory waterfowl and resident birds are consuming food that can exceed the 2.8 to 3.0 mg/kg DDE (WW) dietary intake shown to have adverse effects on waterfowl as well as National Academy of Sciences guidelines for predators (1.0 mg/kg WW, freshwater species; 0.05 mg/kg WW, saltwater species). Birds of prey and piscivorous birds, such as the endangered California brown pelican, are at the greatest risk of eggshell thinning as a result of DDE bioaccumulation. Birds, such as the white-faced ibis, feeding in agricultural fields also may be of concern.

DDE concentrations in biota collected as part of this investigation and other studies done in the Salton Sea area have documented some of the highest levels in California. However, on the basis of DDE/DDT ratios and DDT/DDE/DDD proportions, little evidence of recent DDT use, was observed in this investigation.

A total of 19 organochlorine pesticides other than DDT and its metabolites were found in biota from the Imperial Valley. Of these, only two, toxaphene and hexachlorobenzene, were detected at concentrations above 1 $\mu g/g$ DW. The most frequently detected organochlorine pesticides were dieldrin in 60 percent of samples and DCDA (dacthal) in 64 percent. No organochlorine pesticide residues above the National Academy of Sciences threshold of 0.1 $\mu g/g$ to protect predatory (piscivorous) birds were found in fish.

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Table 1. *Subsurface-drainwater sampling sites in the Imperial Valley, May 1988*

[Local identifier is Imperial Irrigation District (IID) designation]

Site No.	Local identifier	Latitude	Longitude
1	S-403	33°18'02"N	115°35'22"W
2	TD-2907	33°18'55"N	115°33'40"W
3	SS-4	33°10'33"N	115°37'09"W
4	S-38	33°10'58"N	115°36'15"W
5	S-45	33°10'10"N	115°37'50"W
6	S-226	33°10'06"N	115°33'21"W
7	S-269	33°10'37"N	115°31'03"W
8	S-417	33°11'30"N	115°33'40"W
9	S-332	33°11'57"N	115°33'39"W
10	TD-2013	33°11'55"N	115°26'55"W
11	SS-3	33°07'30"N	115°46'58"W
12	SS-26	33°09'15"N	115°48'15"W
13	S-219	33°04'53"N	115°41'57"W
14	S-337	33°04'55"N	115°42'30"W
15	SS-11	33°08'23"N	115°39'19"W
16	S-43	33°09'42"N	115°37'48"W
17	S-57	33°06'53"N	115°34'42"W
18	TD-1829	33°04'55"N	115°34'40"W
19	S-25	33°06'15"N	115°33'39"W
20	S-79	33°07'30"N	115°32'33"W
21	S-119	33°08'22"N	115°30'26"W
22	S-243	33°05'18"N	115°29'00"W
23	S-488	33°05'18"N	115°27'26"W
24	TD-3038	33°08'30"N	115°22'55"W
25	TD-2715	33°07'10"N	115°24'55"W
26	TD-147	33°04'55"N	115°23'20"W
27	S-364	33°02'03"N	115°42'19"W
28	S-28	32°59'18"N	115°37'07"W
29	S-69	33°00'23"N	115°37'13"W
30	S-94	33°02'12"N	115°38'45"W
31	S-127	33°01'15"N	115°36'10"
32	S-353	33°03'28"N	115°34'36"W
33	S-142	33°04'26"N	115°29'39"W
34	S-175	33°01'45"N	115°33'52"W
35	S-290	33°02'12"N	115°30'29"W
36	S-214	33°03'04"N	115°28'44"W
37	S-385	33°00'27"N	115°29'26"W
38	S-122	32°58'52"N	115°26'51"W
39	S-160	33°03'05"N	115°27'25"W
40	S-212	33°03'04"N	115°27'53"W
41	S-241	33°04'26"N	115°27'53"W
42	S-383	33°03'33"N	115°26'21"W
43	TD-245	33°01'20"N	115°20'40"W
44	S-230	32°58'23"N	115°40'31"W
45	S-55	32°57'00"N	115°36'40"W
46	S-256	32°54'25"N	115°38'00"W
47	S-295	32°56'17"N	115°38'58"W
48	S-112	32°55'33"N	115°37'43"W
49	S-424	32°53'55"N	115°38'00"W
50	S-154	32°53'54"N	115°31'01"W
51	S-105	32°56'55"N	115°32'20"W
52	S-133	32°57'25"N	115°32'10"W
53	S-153	32°55'39"N	115°32'07"W
54	S-365	32°57'21"N	115°28'25"W
55	TD-2001	32°55'55"N	115°22'59"W
56	TD-2040	32°55'00"N	115°25'40"W
57	TD-2554	32°55'25"N	115°20'05"W
58	S-322	32°54'57"N	115°18'36"W
59	S-396	32°56'16"N	115°18'36"W
60	TD-2432	32°49'12"N	115°46'09"W
61	S-70	32°52'43"N	115°41'46"W
62	S-68	32°51'07"N	115°44'23"W
63	S-333	32°51'06"N	115°43'35"W
64	S-110	32°50'48"N	115°35'17"W
65	S-67	32°52'07"N	115°35'35"W
66	S-225	32°49'04"N	115°35'09"W
67	S-265	32°48'26"N	115°40'12"W
68	S-398	32°49'56"N	115°39'11"W
69	S-148	32°52'06"N	115°30'03"W
70	TD-1408	32°49'30"N	115°29'46"W
71	S-234	32°49'55"N	115°32'37"W
72	S-410	32°51'15"N	115°32'10"W
73	S-411	32°51'40"N	115°33'10"W
74	S-2	32°52'30"N	115°23'45"W
75	S-4	32°52'30"N	115°22'30"W
76	S-103	32°48'55"N	115°27'23"W
77	S-247	32°50'48"N	115°27'04"W
78	S-376	32°52'13"N	115°27'19"W
79	S-72	32°50'21"N	115°21'16"W
80	S-169	32°48'09"N	115°17'32"W
81	S-187	32°48'12"N	115°21'51"W
82	S-21	32°47'29"N	115°45'52"W
83	S-22	32°47'52"N	115°45'07"W
84	S-130	32°48'02"N	115°45'46"W
85	S-207	32°44'40"N	115°43'47"W
86	TD-2939	32°42'25"N	115°45'10"W
87	S-352	32°45'28"N	115°43'31"W
88	S-81	32°42'59"N	115°41'10"W
89	S-113	32°45'11"N	115°35'08"W
90	S-115	32°45'33"N	115°37'10"W
91	S-242	32°47'05"N	115°38'45"W
92	S-392	32°47'20"N	115°35'00"W
93	S-423	32°42'59"N	115°37'38"W
94	S-93	32°43'20"N	115°29'30"W
95	S-221	32°45'58"N	115°30'43"W
96	S-229	32°44'14"N	115°29'43"W
97	S-321	32°43'22"N	115°32'30"W
98	S-371	32°44'42"N	115°32'35"W
99	S-144	32°45'04"N	115°24'43"W
100	S-164	32°45'58"N	115°27'19"W
101	S-202	32°43'46"N	115°24'44"W
102	S-368	32°46'19"N	115°24'41"W
103	S-408	32°43'20"N	115°27'50"W
104	S-176	32°45'55"N	115°19'10"W
105	S-316	32°45'04"N	115°18'59"W
106	S-336	32°43'20"N	115°20'40"W
107	S-386	32°44'38"N	115°17'34"W
108	S-393	32°44'02"N	115°16'15"W
109	S-60	32°39'26"N	115°37'10"W
110	S-344	32°40'18"N	115°39'16"W
111	S-416	32°42'16"N	115°38'16"W
112	S-108	32°41'58"N	115°31'25"W
113	S-182	32°42'29"N	115°29'48"W
114	S-402	32°39'38"N	115°34'33"W
115	S-59	32°40'27"N	115°27'21"W
116	S-267	32°40'45"N	115°24'26"W
117	S-14	32°42'03"N	115°20'57"W
118	S-360	32°41'19"N	115°29'40"W
119	S-222	32°42'19"N	115°15'58"W

Table 2.--*Biological sampling sites and sampled constituents for the detailed investigation of the Salton Sea area*

[Constituents: TE, trace elements; OC, organochlorine pesticides. Location of sites shown in figure 10]

Site No.	Description or designation	Constituents
	Salton Sea	
B1	Salton Sea National Wildlife Refuge Unit 1	TE
B2	Poe Road	TE
B3	Salton Sea Test Base	TE
B4	Salton City	TE
B5	Salton Sea Beach	TE
B6	Desert Shores	TE
B7	Desert Beach	TE
B8	Bob's Playa River Marina	TE
B9	Bombay Beach	TE
B10	S Drain Outlet	TE+OC
B11	Alamo River delta	TE+OC
B12	Red Hill Marina	TE
B13	Vail 4 Drain Outlet	TE+OC
B14	Obsidian Butte	TE
B15	Bowles Road	TE
B16	New River delta	TE+OC
	Rivers and creeks	
B17	New River at Rio Bend	TE+OC
B18	Alamo River at Garst Road	TE+OC
B19	San Felipe Creek	TE
B20	Salt Creek	TE
B21	Colorado River at Palo Verde	TE+OC
	Drainwater ditches	
B22	Trifolium 13	TE+OC
B23	Trifolium 14	TE+OC
B24	Vail Cutoff	TE+OC
B25	Vail 2A	TE+OC
B26	Vail 4	TE+OC
B27	Vail 4A	TE+OC
B28	Vail 5	TE+OC
B29	S	TE
B30	Z	TE
B31	81st Street	TE
B32	Johnson Street	TE
	Freshwater impoundments	
B33	Shady Acres Duck Club	TE+OC
B34	D and K Duck Club	TE+OC
B35	RH Pond	TE+OC
B36	HQ Pond	TE+OC
B37	Reidman Pond	TE+OC
B38	Hazard Pond	TE+OC
	Imperial Valley	
B39	South Brawley	B/TE+OC
B40	McKendry Road	B/TE+OC

Table 3.--*Samples collected from biological sites in the Salton Sea area, 1988-90*

[Sites described in table 2]

Common name (species)	Sample	Sites	Number of samples analyzed for: Trace elements	Pesticides
Vegetation				
Filamentous green alga (*Chaetomorpha* sp.)	Composite	B1,B3,B4,B5, B6,B7,B8,B9, B12,B14,B15,B32	12	0
Tubular green alga (*Enteromorpha* sp.)	Composite	B1,B2,B3,B4, B5,B6,B7,B8, B9,B12,B14, B15,B31	13	0
Blue-green alga (*Myxophyceae* sp.)	Composite	B32	1	0
Common cattail (*Typha latifolia*)	Whole plant	B19,B20,B30, B31,B32	5	0
Invertebrates				
Pileworm (*Nereis succinea*)	Composite	B11,B13	8	2
Waterboatman (*Corixa* sp.)	Composite	B11,B16	3	3
Pelagic invertebrate "mixture"	Composite	B18,B23	2	0
Crayfish (*Procambraus clarkii*)	Whole body	B11,B16	2	2
Asiatic river clam (*Corbicula fluminea*)	Whole-body composite (Soft tissue only)	B16,B21,B22 B23,B24,B30, B32	16	12

Table 3.--*Samples collected from biological sites in the Salton Sea area, 1988-90*--Continued

Common name (species)	Sample	Sites	Number of samples analyzed for: Trace elements	Pesticides
		Fish		
Mosquitofish (*Gambusia affinis*)	Whole body	B17,B19,B20, B31,B32	5	1
Sailfin molly (*Poecilia latipinna*)	Whole body	B17,B19,B20, B31,B32	6	0
Mudsucker (*Gillichthys mirablis*)	Whole body	B16	1	0
Bairdiella (*Bairdiella icistius*)	Whole body	B10	5	5
		Amphibians		
Bullfrog (*Rana catesbeiana*)	Whole body	B18	2	2
		Reptiles		
Spiny softshelled turtle (*Trionyx spineferus*)	Fat/liver/ egg	B26,B39	6	7
		Birds		
Black-necked stilt (*Himantopus mexicanus*)	Carcass/ egg	B11,B16,B17, B23,B29,B35, B37,B38,B40	137	123
American coot (*Fulica americana*)	Liver	B23	3	3
Ruddy duck (*Oxypura jamaicensis*)	Liver/ muscle	B1,B13,B24, B36,B38	71	27
Eared grebe (*Policeps caspicus*)	Liver/ muscle	B14,B16	5	5
Northern shoveler (*Anus clypeatea*)	Liver/ muscle	B11,B33,B37, B38	25	3
White-faced ibis (*Plegadis chihi*)	Liver/ muscle	B47	9	9
Yuma clapper rail (*Rallus longirostris yumaiensis*)	Carcass	B29	1	0

Table 4.--*Summary of laboratories, types of analyses performed, year(s) analyses were performed, and sample medium analyzed in the Salton Sea detailed investigation*

[Analysis: ICP, Inductively coupled plasma scan for trace elements (including boron); AA, Atomic absorption spectroscopy for arsenic, mercury, and selenium; OC, Organochlorine pesticide scan includes DDT, DDE, DDD, dieldrin, hexachlorobenzene, and toxaphene]

Laboratory	Analysis	Year	Media
Environmental Trace Substances Research Center	ICP,AA	1988	Bird
		1989	Vegetation, invertebrate, fish, amphibian, reptile, bird
Hazleton Laboratory America	ICP,AA	1988	Invertebrate, fish
		1989	Bird
Mississippi State Chemistry Laboratory	OC	1988	Bird
		1989	Invertebrate, fish, amphibian, reptile, bird
Patuxent Analytical Control Facility	ICP,AA,OC	1990	Vegetation, invertebrate, fish
Texas A&M Research Foundation	OC	1988	Invertebrate, fish, bird
Weyerhauser Analytical and Testing Services	OC	1987	Invertebrate, fish, bird

Table 5.--*Highest acceptable detection limits of irrigation drainwater contaminants for biotic samples in the detailed investigation*

[Concentrations in micrograms per gram, wet weight]

Analytical technique and contaminant	Detection limit[1]
Organochlorine scan	
DDT, DDE, DDD	0.10
toxaphene	.50
Inductively coupled plasma emission spectroscopy	
boron	
without preconcentration	20
with preconcentration	4
Hydride generation atomic absorption spectroscopy	
arsenic	.8
selenium	.2
Cold vapor reduction atomic absorption spectroscopy	
mercury	.1

[1]Detection limits are greatly affected by sample size.

Table 6.--*Acceptable accuracy and precision guidelines for chemical analyses biotic samples*

[Method: ICP, inductively coupled plasma scan: AA, atomic-absorption spectrometry; GC, gas chromatography]

Method	Recovery range	±95 percent confidence interval: Region of detection[1]	±95 percent confidence interval: Region of quantization[2]
ICP	80-120%	30%	15%
AA	85-115%	20%	10%
GC	80-120%	30%	15%

[1]Duplicate analyses fall within the region of detection when their average concentration is between 2 and 10 times the limit of detection. If the average of the duplicate analyses is less than 2 times the limit of detection, no evaluation of the precision is made. The confidence interval is defined to be +2 times the limit of detection.

[2]Duplicate analyses fall within the region of quantitation when their average concentration is greater than 10 times the limit of detection.

Table 7.--*Summary statistics for selected constituents in monthly samples of water from 15 subsurface drains in the Imperial Valley, August 1988-August 1989*

[Average values in italics are for May 1988 sampling. µg/L, microgram per liter; lb/yr, pound per year]

Site (sump No.)	Selenium concentration		Selenium/chloride ratio		Selenium load (lb/yr)
	Average (µg/L)	Range (µg/L)	Average	R-square value	
S-72	61 ±18.8 *68*	28 to 88	0.04 ±0.01 *0.027*	52	29
S-371	94 ±30 *76*	43 to 140	.033 ±.005 *.033*	87	22.3
S-176	50 ±11.5 *51*	41 to 86	.027 ±.004 *.023*	83	21.5
S-154	19 ±6.7 *15*	2 to 29	.003 ±.001 *.0033*	51	0.4
S-344	51 ±9.7 *60*	36 to 68	.016 ±.002 *.016*	68	7.6
S-423	158 ±56 *240*	68 to 240	.04 ±.003 *.038*	96	1.3
S-417	184 ±99 *300*	19 to 340	.019 ±.004 *.018*	92	16.7
S-142	13.5 ±2 *16*	11 to 17	.047 ±.012 *.073*	1.9	([1])
S-4	130 ±25 *170*	91 to 170	.016 ±.002 *.018*	58	21.2
S-265	78 ±17 *76*	50 to 99	.036 ±.011 *.04*	<1	55
S-352	42 ±19 *65*	12 to 65	.02 ±.014 *.011*	90	4.2
S-226	267 ±75 *250*	71 to 360	.025 ±.007 *.023*	28	40.9
S-269	267 ±44 *230*	180 to 360	.03 ±.01 *.029*	3	54.6
S-94	35 ±16 *51*	17 to 67	.011 ±.006 *.009*	96	5.5
S-241	45 ±16 *30*	13 to 70	.016 ±.003 *.025*	88	4.2

[1]No flow observed.

Table 8.--*Summary statistics for selected dissolved constituents in water from five sites in the Imperial Valley, August 1988-August 1989*

[μg/L, microgram per liter; mg/L, milligram per liter; --, no data]

Site	Selenium concentration (μg/L)			Selenium/ chloride ratio	Dissolved-solids concentration (mg/L)	Selenium load (ton/yr)
	Median	Minimum	Maximum			
East Highline Canal	2 ±0.3	2	3	0.022 ±.0035	686 ±41	--
Alamo River at international boundary	4.5 ±2.6	3	10	.0042 ±.004	3,690 ±501	--
New River at international boundary	2 ±0.5	1	2	.0015 ±.0006	2,670 ±362	0.5
Alamo River at outlet to Salton Sea	8 ±2.1	2	10	.017 ±.0026	2,170 ±159	6.5
New River at outlet to Salton Sea	4 ±0.5	4	5	.0045 ±.0006	2,835 ±130	2.5
Trifolium Drain 1	6 ±2	5	10	.012 ±.033	2,350 ±798	--

Resident shorebirds such as the black-necked stilt show elevated concentrations of DDE in carcass and eggs with an apparently small dietary intake of only 0.01 to 0.02 μg/g WW. The resultant bioaccumulation factor in body tissues is as great as 1,200 times. There is concern that if stilts are adversely affected by DDE even though DDE levels in their food were low, more environmentally sensitive species such as the endangered Yuma clapper rail may also be effected. Declines in colonial water-bird populations, on the basis of thresholds and guidelines established for piscivorous birds, may be related to elevated DDE concentrations and other drainwater contaminants. Gulls and mammals (such as the raccoon) that eat bird eggs and fish also are being exposed to some of the highest DDE concentrations found in the Imperial Valley. Typically, aquatic species are more sensitive to DDE contamination (National Academy of Sciences, 1973). However; there is evidence that birds feeding primarily in the agricultural fields also are accumulating elevated levels of DDE. Resident birds of concern are white-faced ibis, cattle egret, and several species of birds of prey.

Table 9.--*Selenium in biota, Salton Sea Area (1988-90)*

[Concentrations in micrograms per gram, dry weight; <, less than indicated detection limit; --, no data; N, number of samples collected; DV, number of samples with detectable values; GM, geometric mean (calculated using 1/2 detection limit when data set has more than 50 percent detectable values)]

	Salton Sea			New and Alamo Rivers and irrigation drains			San Felipe and Salt Creeks		
Sample type	N/DV	GM	Range	N/DV	GM	Range	N/DV	GM	Range
AQUATIC VEGETATION									
Blue-green algae	1/1	1.8	<0.71-1.7	--	--	--	--	--	--
Filamentous green algae	12/10	0.9	<.71-1.7	--	--	--	--	--	--
Enteromorpha	13/8	0.7	<.58-1.3	--	--	--	--	--	--
EMERGENT VEGETATION									
Cattail	--	--	--	3/0	--	<64	2/1	--	<0.62-1.1
INVERTEBRATES									
Asiatic river clam	--	--	--	5/5	4.4	2.6-6.4	--	--	--
Waterboatman	3/3	2.1	1.4-3.3	--	--	--	--	--	--
Pileworm	8/8	3.1	0.8-12.1	--	--	--	--	--	--
Amphipod, pileworm, waterboatman composite	2/2	2.8	2.6-3.1	--	--	--	--	--	--
Crayfish	--	--	--	2/2	3.1	2.4-3.3	--	--	--
FORAGE FISH									
Mosquito fish	--	--	--	3/3	3.5	2.6-4.7	2/2	6.9	6.4-7.4
Sailfin molly	--	--	--	4/4	3.9	2.5-5.8	2/2	6.4	5.5-7.4
Longjaw mudsucker	1/1	6.1	--	--	--	--	--	--	--
Bairdiella	5/5	12.9	12.0-16.0	--	--	--	--	--	--
AMPHIBIANS AND REPTILES									
Bullfrog	--	--	--	2/2	4.4	3.6-5.4	--	--	--
Spiny softshelled turtle	--	--	--	6/6	10.3	8.0-14.0	--	--	--
WATER BIRDS - RESIDENT									
Black-necked stilt									
(egg)	127/127	4.3	1.6-3.5	--	--	--	--	--	--
(carcass)	19/19	5.4	3.2-11.3	--	--	--	--	--	--
Coot (liver)	--	--	--	3/3	10.3	7.9-16.3	--	--	--
Yuma clapper rail	--	--	--	1/1	4.8	--	--	--	--
WATER BIRDS - MIGRATORY									
Ruddy duck									
(liver)	57/57	11.7	5.2-41.5	--	--	--	--	--	--
(muscle)	17/17	--	2.7-7.2	--	--	--	--	--	--
Northern shoveler									
(liver)	--	--	--	19/19	19.1	9.1-47.0	--	--	--
(muscle)	--	--	--	6/6	5.2	3.8-12.0	--	--	--
White-faced ibis									
(carcass)	--	--	--	9/9	5.3	3.9-6.6	--	--	--
(liver)	--	--	--	9/9	7.4	5-13.2	--	--	--
Eared grebe (liver)	5/5	12.7	2.7-35.1	--	--	--	--	--	--

Table 10.--*Selenium concentrations in algae from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR) and Volta Wildlife Management Area (WMA) are from Schuler, 1987. Values for Fernley Wildlife Management Area (WMA) are from Hoffman and others, 1990. Salton Sea values are from this detailed study. ND, not detected.]

Location	Number of Samples	Geometric Mean	Range
Salton Sea area	12	0.9	(ND-1.7)
Kesterson NWR	9	30.9	(14-120)
Fernley WMA	6	1.4	(ND-2.2)
Volta WMA	6	0.3	(ND-0.5)

Table 11.--*Selenium concentrations in cattail from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR) and Volta Wildlife Management Area (WMA) are for leaves only (from Schuler, 1987). Values for Fernley Wildlife Management Area (WMA) are for leaves only (from Hoffman and others, 1990). Values for Salton Sea are for whole plants from this detailed study. ND, not detected; <, less than quantitation limit; --, not determined]

Location	Number of samples	Geometric mean	Range
Salton Sea area			
Major agricultural drains	3	<0.6	--
San Felipe and Salt Creeks	2	--	(ND-1.1)
Kesterson NWR	12	37.2	(17-160)
Fernley WMA	3	<.8	--
Volta WMA	6	0.6	(ND-1.2)

Table 12.--*Selenium concentrations in waterboatman from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR) and Volta Wildlife Management Area (WMA) are from Schuler, 1987. Values for Fernley Wildlife Management Area (WMA) are from Hoffman and others, 1990. Salton Sea values are from this detailed study. ND, not detected]

Location	Number of samples	Geometric mean	Range
Salton Sea area	3	2.1	(1.4-3.3)
Kesterson NWR	18	18.6	(5.9-130)
Fernley WMA	2	4.1	(3.5-4.7)
Volta WMA	9	1.6	(1.1-1.9)

Table 13.--*Selenium concentrations in mosquitofish from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR) and Volta Wildlife Management Area (WMA), North Grasslands are from Ohlendorf and others, 1987. Values for Fernley Wildlife Management Area (WMA) are from Hoffman and others, 1990. All other values are from the Salton Sea agricultural drainwater study]

Location	Number of samples	Geometric mean	Range
Salton Sea area			
Major agricultural drains	2	10.8	7.3-16
San Felipe and Salt Creeks	2	6.9	6.4-7.4
Minor agricultural drains	3	3.5	2.6-4.7
Kesterson NWR	12	226	90-430
North Grasslands	6	7.0	5.4-8.6
Fernley WMA	2	4.2	3.9-4.4
Volta WMA	3	1.9	1.2-3.0

?

Table 14.--*Selenium concentrations in black-necked stilt eggs from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR), Volta Wildlife Management Area (WMA), and Grasslands Water District (WD) are from Ohlendorf and others, 1987. Salton Sea values are from this detailed study]

Location	Number of samples	Geometric mean	Range
Salton Sea area	128	4.3	(1.6-35)
Kesterson NWR	37	24.8	(5.2-64)
Grasslands WD	6	4.7	(3.8-5.7)
Volta WMA	10	2.4	(1.6-3.4)

Table 15.--*Selenium concentrations in black-necked stilt livers from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR), South and North Grasslands and Volta Wildlife Management Area (WMA) are from Ohlendorf and others, 1987. Salton Sea values are from Setmire and others, 1990]

Location	Number of samples	Geometric mean	Range
Salton Sea area	12	21.7	(19-27)
Kesterson NWR	9	46.4	(19-80)
South Grasslands	13	35.6	(9.7-53)
North Grasslands	10	12.7	(4.3-41)
Volta WMA	4	7.8	(6.3-9.9)

>

Table 16.--*Selenium concentrations in coot livers from Salton Sea area and other locations*

[Concentrations in micrograms per gram, dry weight. Values for Kesterson National Wildlife Refuge (NWR), South and North Grasslands Water Districts (WD) and Volta Wildlife Management Area (WMA) are from Ohlendorf and others, 1987. Salton Sea values are from this detailed study and Setmire and others, 1990]

Location	Number of samples	Geometric mean	Range
Salton Sea area	7	12.3	(7.9-2)
Kesterson NWR	23	81.5	(19-160)
South Grasslands WD	5	23.3	(17-30)
North Grasslands WD	5	11.9	(7.0-28)
Volta WMA	12	5.4	(1.8-14)

Table 17.--*Boron in biota from the Salton Sea Area (1986-90)*

[Concentrations in micrograms per gram, dry weight; <, less than indicated detection limit; --, no data; N, number of samples collected; ND, number of samples with detectable values; GM, geometric mean (non-detected values calculated using 1/2 detection limit when data set has more than 50 percent detectable values)]

	Salton Sea			New and Alamo Rivers and irrigation drains			San Felipe and Salt Creeks		
Sample type	N/DV	GM	Range	N/DV	GM	Range	N/DV	GM	Range
AQUATIC VEGETATION									
Blue-green algae	1/1	270	--	--	--	--	--	--	--
Filamentous green algae	12/11	170	<65-390	--	--	--	--	--	--
Enteromorpha	13/10	115	<55-230	--	--	--	--	--	--
EMERGENT VEGETATION									
Cattail	--	--	--	3/0	--	<75	2/2	104.4	99-110
INVERTEBRATES									
Pileworm	8/7	70.2	22-160	--	--	--	--	--	--
Waterboatman	3/1	13.4	10-21	--	--	--	--	--	--
Invertebrate composite[1]	1/1	21.0	--	--	--	--	--	--	--
Invertebrate composite[2]	1/1	20.0	--	--	--	--	--	--	--
Asiatic river clam	--	--	--	5/0	--	<29.2	--	--	--
Crayfish	--	--	--	2/0	--	<23.9	--	--	--
FISH									
Mosquitofish	--	--	--	3/0	--	<22.1	2/0	--	<45
Sailfin molly	--	--	--	4/0	--	<18.2	2/0	--	<13
Longjaw mudsucker	1/0	--	<25.3	--	--	--	--	--	--
Bairdiella	5/5	6.2	5.0-8.3	--	--	--	--	--	
AMPHIBIANS AND REPTILES									
Bullfrog	--	--	--	2/2	3.9	3-5	--	--	--
Spiny softshelled turtle	--	--	--	6/6	2.7	2-5	--	--	--
BIRDS - MIGRATORY									
Ruddy duck									
(liver)	54/42	2.7	<2-7.3	--	--	--	--	--	--
(muscle)	17/6	--	<2-4	--	--	--	--	--	--
Northern shoveler									
(liver)	--	--	--	19/18	3.9	<2-6.3	--	--	--
(muscle)	--	--	--	6/2	--	<2-3	--	--	--
White-faced ibis									
(liver)	--	--	--	9/0	--	<1.7	--	--	--
(muscle)	--	--	--	9/1	--	<3-3	--	--	--
Eared grebe									
(liver)	5/1	--	<2-2	--	--	--	--	--	--
BIRDS - RESIDENT									
Black-necked stilt									
(egg)	83/30	1.8	<2-6.0	--	--	--	--	--	--
(muscle)	19/18	3.0	<2-6.6	--	--	--	--	--	--
American coot									
(liver)	--	--	--	3/1	--	<3-4	--	--	--
BIRDS-ENDANGERED									
Yuma clapper rail	--	--	--	1/1	14.0	--	--	--	--

[1] Waterboatmen and amphipods.
[2] Waterboatmen, amphipods, and pileworms.

Table 18.--*Comparison of boron concentration in filamentous algae at Salton Sea area and other locations*

[Concentrations are in micrograms per gram, dry weight. Values for Stillwater Wildlife Management Area (WMA) reconnaissance investigation (Carson Lake) and background location (Carson Valley) from Hoffman and others (1990b) and for Kesterson National Wildlife Refuge (NWR) and Volta Wildlife Management Area from Schuler (1987). N, number of samples analyzed; DV, number of samples with detectable values; --, not determined]

Location	N/DV	Geometric mean	Range
Salton Sea area	12/11	270	<65-390
Stillwater WMA			
Carson Lake	13/13	--	110-410
Carson Valley	3/0	--	<40.0-<81.0
Kesterson NWR	9/9	501	390-787
Volta WMA	6/6	85.1	64-140

Table 19.--*Comparison of boron concentration in submerged aquatic vegetation collected at Salton Sea area and other locations*

[Concentrations are in micrograms per gram, dry weight. Values for Salton Sea from Setmire and others (1990), Kesterson National Wildlife Refuge (NWR) from Schuler (1987), and Stillwater Wildlife Management Area (WMA) and Carson Lake from Hoffman and others (1990b). N, number of samples analyzed; DV, number of samples with detectable values; --, not determined]

Location	N/DV	Geometric mean	Range
Salton Sea area	1/1	370	370
Kesterson NWR	21/21	371	120-780
Stillwater WMA	8/7	--	<5.6-1,200
Carson Lake	8/8	--	76.5-539

Table 20.--*Levels of boron in female ruddy duck livers, Salton Sea, 1988-89*

[Concentrations in micrograms per gram, dry weight; <, less than indicated detection limit; N, number of samples collected; ND, number of samples with detectable values; GM, geometric mean (non-detected values calculated using 1/2 detection limit when data set has more than 50 percent detectable values); --, determined]

Sample period	N/DV	Geometric mean	Range
November 1988	11/1	--	<3-4
December 1988	10/0	--	<3
March 1989	12/11	3.3	<2-6.6

Table 21.--*Total DDT in biota from the Salton Sea area. 1986-90*

[Concentrations in micrograms per gram, dry weight; --, no data; N, number of samples collected: DV, number of samples with detectable values; GM, geometric mean (calculated using 1/2 detection limit when data set has more than 50 percent detectable values)]

Sample type	New and Alamo Rivers and irrigation drains			Salton Sea		
	N/DV	GM	Range	N/DV	GM	Range
INVERTEBRATES						
Asiatic river clam	--	--	--	12/11	.32	0.13-5.74
Crayfish	--	--	--	4/4	.31	0.1-0.68
Waterboatman	5/5	.04	.01-.07	--	--	--
Pileworm	2/2	.04	.03-.04	--	--	--
FISH						
Mosquitofish	--	--	--	3/3	.59	.57-.61
Sailfin molly	--	--	--	5/5	.22	.14-.35
Red shiner	--	--	--	1/1	5.82	
Bairdiella	5/5	.10	.08-.12	--	--	--
Tilapia	12/12	.25	.07-.41	--	--	--
Corvina (fillet)	1/1	.09	--	--	--	
AMPHIBIANS AND REPTILES						
Bullfrog	--	--	--	2/2	.06	.01-.38
Spiny softshelled turtle						
(fat)	--	--	--	6/6	15.20	11.21-21.89
(eggs)	--	--	--	1/1	7.96	-
BIRDS-MIGRATORY						
Northern shoveler (breast)	--	--	--	6/6	.58	.17-2.14
Ruddy duck (breast)	30/30	.27	.096-1.55	--	--	--
Eared grebe (breast)	5/5	.28	.17-1.1	--	--	--
White-faced ibis						
(fat)	--	--	--	9/9	5.79	3.9-11.72
(liver)	--	--	--	9/9	6.06	3.14-9.85
BIRDS-RESIDENT						
Black-necked stilt						
(carcass)	38/38	.69	.02-2.76	--	--	--
(egg)	84/84	2.57	.05-12.1	--	--	--
American coot						
(liver)	--	--	--	3/3	.01	.01-.03
(breast)	--	--	--	4/4	.22	.09-.45
Double-crested cormorant						
(breast)	3/3	1.1	.38-4.92	--	--	--
Cattle egret	--	--	--	2/2	2.32	2.21-2.43
Herring gull	1/1	2.81		--	--	--
Barn owl (breast)	--	--	--	1/1	2.71	
Great blue heron (breast)	--		--	--	-1/1	13.03

Table 22.--*p,p'-DDE in biota from the Salton Sea area, 1986-1990*

[Concentrations in micrograms per gram, dry weight; --, no data; N, number of samples collected; DV, number of samples with detectable values; GM, geometric mean (calculated using 1/2 detection limit when data set has more than 50 percent detectable values)]

Sample type	New and Alamo Rivers and irrigation drains			Salton Sea		
	N/DV	GM	Range	N/DV	GM	Range
INVERTEBRATES						
Asiatic river clam	--	--	--	12/11	.30	.013-5.5
Crayfish	--	--	--	4/4	.31	.01-.68
Waterboatman	5/5	.04	.01-.07	--	-	--
Pileworm	2/2	.04	.03-.04	--	--	--
FISH						
Mosquitofish	--	--	--	3/3	.58	.54-.61
Sailfin molly	--	--	--	5/5	.21	.14-.35
Red shiner	--	--	--	1/1	5.70	--
Bairdiella	5/5	.10	.08-.12	--	--	--
Tilapia	12/12	.23	.07-.37	--	--	--
Corvina (fillet only)	1/1	.07	--	--	--	--
AMPHIBIANS AND REPTILES						
Bullfrog	--	--	--	2/2	.06	.01-.38
Spiny softshelled turtle						
(fat)	--	--	--	6/6	14.80	11.00-21.00
(eggs)	--	--	--	1/1	7.80	--
BIRDS-MIGRATORY						
Northern shoveler (breast)	--	--	--	6/6	.55	.17-2.10
Ruddy duck (breast)	30/30	.26	.096-1.50	--	--	--
Eared grebe (breast)	5/5	.28	.17-1.10	--	--	--
White-faced ibis						
(fat)	--	--	--	9/9	5.57	3.70-11.0
(liver)	--	--	--	9/9	5.93	3.10-9.60
BIRDS-RESIDENT						
Black-necked stilt						
(egg)	84/84	2.54	.05-12.0	--	--	--
(body)	38/38	.69	.02-2.76			
American coot						
(liver)	3/3	.014	.01-.03			
(breast)				4/4	.22	.09-.45
Double-crested cormorant						
(breast)	3/3	1.13	.38-4.90	--	--	--
Cattle egret	--	--	--	2/2	2.3	2.20-2.40
Herring gull	1/1	2.80		--	--	--
Barn owl (breast)	--	--	--	1/1	2.7	
Great blue heron (breast)	--	--	--	1/1	13.0	

Table 23.--*Comparison of p,p'-DDE concentrations in mosquitofish from California drainwater areas and fish from the National contaminant Biomonitoring Program.*

[Concentrations in micrograms per gram, wet weight. TSMP (Toxic Substances Monitoring Program) values from SWQCB (1990); Tulare Basin values from Schroeder and others (1988), and values for NCBP (National Contaminant Biomonitoring Program) from Schmitt and others (1985, 1990); GM, geometric mean; ND, not detected]

[Authors: Not in ref. list. Also, i[f] used, it's how[...] be spelled ou[t] as "Califor[nia] State Water Qu[ality] Control Board 1990)." E]

Location	GM	Range
Salton Sea Area		
Detailed investigation	0.58	0.54-0.61
TSMP	1.10	(one composite)
Tulare Basin	0.14	0.10-0.34
NCBP 1981	0.20	0.01-2.57
NCBP 1984	0.19	ND-4.74

Table 24.--*Comparison of p,p'-DDE concentrations in cormorant tissues (muscle and carcass) from contaminated sites* in the Western United States

[Concentrations in micrograms per gram, wet weight. Values for Houston Shipping Channel from King (1989a) and lower Colorado River from Radtke and others (1988). N, number of samples analyzed; DV, number of samples with detectable values; GM, geometric mean; --, not determined]

Species	Location	N/DV	GM	Range
Double-crested cormorant	Salton Sea	3/3	1.13	0.38-4.9
Olivaceous cormorant	Houston Shipping Channel	10/10	.80	0.20-2.5
Double-crested cormorant	Houston Shipping Channel	10/10	.93	0.40-2.3
Double-crested cormorant	Lower Colorado River	3/3	--	2.10-6.6

Table 25.--*Colonial water-bird survey of active nests at rookery areas along the south and southeast shores of the Salton Sea*

Species	Number of active nests			
	1987	1988	1989	1990
Great blue heron	246	208	0	15
Cattle egret	1,373	850	98	0
Snowy egret	9	3	80	0
Great egret	85	8	53	4
Double-crested cormorant	63	57	0	0
Total	1,776	1,126	231	19

Table 26.--*Concentrations of selected organochlorine pesticides in biological samples collected from the Salton Sea area and Imperial Valley, 1986-90*

[Concentrations in milligrams per gram (parts per million) wet weight. <, less than indicated analytical detection limit]

Compound	Number of samples analyzed	Samples with detectable residue		Concentration (range)
		Number	Percent	
Aldrin	37	1	2.7	<0.0-0.01
Oxychlordane	269	96	35.7	<0.01-0.64
gammachlordane	269	8	3.0	<0.01-0.08
alphachlordane	269	39	14.5	<0.01-0.24
Dieldrin	269	162	6.01	0.01-0.85
Endosulfan I	11	1	9.1	<0.01-0.01
Endosulfan II	11	1	9.1	<0.01-0.02
Endosulfan sulfate	11	1	9.1	<0.01-0.02
Endrin	269	9	3.3	<0.01-0.03
Heptachlor	269	0	0.0	<0.01
Heptachlor epoxide	269	50	18.6	<0.01-0.06
Methoxychlor	11	3	27.3	<0.01-0.03
Toxaphene	269	21	7.8	<0.01-7.0
Hexachlorobenzene	223	100	44.8	<0.01-2.9
Alpha-BHC	223	0	0	<0.01
Beta-BHC	223	80	35.9	<0.01-0.36
Gamma-BHC (lineane)	223	0	0.0	<0.01
Delta-BHC	223	2	0.9	<0.01-0.05
Trans-nonachlor	269	55	20.4	<0.01-0.29
Cis-nonachlor	269	8	3.0	<0.01-0.11
Mirex	223	4	1.7	<0.01-0.04
DCPA	11	7	63.6	<0.01-0.32
Dicofol	11	0	0	<0.01
Tetradifon	11	0	0	<0.01

Table 27.--*Summary of agriculture-related contaminants of concern for birds subject to potential adverse effects, Salton Sea area*

[Status: R, resident bird; M, regular migrant bird; B, breeding status in Salton Sea area (status codes--d, recent decline; h, historical; r, rare; ✓, common. Feeding habitat: S, Salton Sea; R/D, river/drain (feeding habitat codes--b, beach or mudflat; f, farmland/fields; h, houses and towns; m, marsh; o, open water; r, riparian; s, shrubland). Number of individuals: ≤, less than or equal to (that is, the number may be as high as indicated value). Agriculture-related contaminants of concern (level of concern): H, high; L, low; --, no concern]

Species	Status			Feeding habitat		Number of individuals	Food items	Agriculture-related contaminants of concern		
	R	M	B	S	R/D			Sc	B	DDE
Pied-billed grebe	✓	✓	✓		m	[1]1,000	Aquatic invertebrates, small fish	H	L	L
Eared grebe	✓	✓	r	o		65,000-1.2 million	Aquatic invertebrates, small fish	H	L	L
Western grebe	✓	✓	✓	o		[1]5,000	Small fish, aquatic invertebrates, amphibians	H	L	L
Clark's grebe	✓	✓	✓	o		[1]500	Small fish, aquatic invertebrates, amphibians	H	L	L
American white pelican	✓	✓	h	o		5,000	Fish	H	--	H
California brown pelican		✓		o		≤5,000	Fish	H	--	H
Double-crested cormorant	✓		d	o		10,000	Fish	H	--	H
American bittern		✓			m	[1]200	Small fish, aquatic invertebrates, small vertebrates	L	--	L
Least bittern	✓	✓	✓		m	[1]550	Small fish, aquatic invertebrates, amphibians	H	--	H
Great blue heron	✓		d	b	m	500	Small fish, crustaceans, frogs, reptiles, aquatic invertebrates	H	--	H
Great egret	✓		d	b	m	300	Small fish, terrestrial insects, small invertebrates	H	--	H
Snowy egret	✓		d	b	m	500-1,000	Small fish, aquatic and terrestrial insects	L	--	H
Cattle egret	✓		d		f,m	[1]30,000	Terrestrial and aquatic insects	H	L	H
Green-backed heron	✓		✓		m	100	Small fish, aquatic and terrestrial insects	H	--	H

Table 27.--*Summary of agriculture-related contaminants of concern for birds subject to potential adverse effects, Salton Sea area* --Continued

Species	Status			Feeding habitat		Number of individuals	Food items	Agriculture-related contaminants of concern		
	R	M	B	S	R/D			Sc	B	DDE
Black-crowned night heron	✓	✓	✓		m	[1]4,000	Small fish, aquatic invertebrates, amphibians	H	--	H
White-faced ibis		✓	r		f,m	[1]20,000	Terrestrial and aquatic invertebrates, grain	L	L	H
Wood stork		✓		b	m	275	Fish, aquatic invertebrates, amphibians	H	--	L
Fulvous whistling duck	✓		r		m	[1]200	Wetland plants, submerged aquatic vegetation	L	H	--
Snow goose		✓			f,m	20,000	Grains, wetland plants	--	L	--
Ross' goose		✓			f,m	10,000	Grains, wetland plants	--	L	--
Canada goose		✓			f,m	5,000	Grains, wetland plants	--	L	--
Green-winged teal		✓			m	10,000	Wetland plants, aquatic invertebrates	L	H	--
Mallard	✓	✓	r		m	400	Wetland plants, aquatic invertebrates, grains	L	H	--
Northern pintail	✓	✓	r		m	20,000	Wetland plants, aquatic invertebrates	L	H	--
Cinnamon teal	✓	✓	r	o	m	3,000	Wetland plants	L	H	--
Northern shoveler		✓		o	m	60,000	Plankton, aquatic invertebrates, wetland plants	H	H	--
Gadwall		✓		o	m	5,000	Wetland plants, aquatic invertebrates	H	H	--
Canvasback		✓		o		900	Aquatic invertebrates, submerged aquatic vegetation	H	H	--
Redhead	✓	✓	✓	o		765	Aquatic invertebrates, submerged aquatic vegetation	H	H	--
Lesser scaup		✓		o		5,000	Aquatic invertebrates, submerged aquatic vegetation	H	H	--
Bufflehead		✓		o	o	360	Aquatic invertebrates, submerged aquatic vegetation	H	H	--
Ruddy duck	✓	✓	✓	o	m	42,000	Aquatic invertebrates, submerged aquatic vegetation	H	H	--
Turkey vulture	✓	✓			f	[1]800	Dead mammals and birds	--	--	H

Table 27.--*Summary of agriculture-related contaminants of concern for birds subject to potential adverse effects, Salton Sea area* --Continued

Species	Status			Feeding habitat		Number of individuals	Food items	Agriculture-related contaminants of concern		
	R	M	B	S	R/D			Se	B	DDE
Osprey		✓		o			Fish	H	--	H
Bald eagle		✓		o	f	≤3	Birds, fish, mammals	H	--	H
Northern harrier		✓			f,m	[1]2,500	Small mammals, birds	--	--	H
Sharp-shinned hawk		✓			r,s	[1]250	Small birds	--	--	L
Cooper's hawk		✓			r,s	[1]300	Small birds	--	--	L
Red-tailed hawk	✓	✓	✓		f	[1]500	Mammals	--	--	L
American kestrel	✓	✓	✓		f,h	[1]4,000	Terrestrial insects, small mammals, small birds	--	--	H
Peregrine falcon		✓		o	m	≤3	Birds	--	--	H
Prairie falcon		✓		o	m	[1]30	Birds	--	--	H
Yuma clapper rail	✓		✓		m	400	Aquatic invertebrates, small fish, amphibians	H	H	L
Virginia rail	✓	✓	✓		m	[1]500	Aquatic invertebrates, small fish	L	L	L
Sora		✓			m	[1]500	Aquatic plants, aquatic invertebrates	L	H	--
Cornmor moorhen	✓	✓	✓		m	[1]3,400	Wetland plants, submarine aquatic vegetation, aquatic invertebrates	L	H	--
American coot	✓	✓	✓	b,o	m	10,000	Wetland plants, algae, aquatic invertebrates	H	H	--
Sandhill crane		✓			f	≤300	Aquatic invertebrates, insects, small mammals	L	--	H
Black-billed plover		✓		b	f	≤1,000	Aquatic and terrestrial invertebrates	L	L	L
Snowy plover	✓	✓	✓	b		115	Aquatic and terrestrial invertebrates	L	H	L
Semipalmated plover		✓		b	f	1,000	Aquatic and terrestrial invertebrates	L	L	L

Table 27.--*Summary of agriculture-related contaminants of concern for birds subject to potential adverse effects, Salton Sea area* --Continued

Species	Status			Feeding habitat		Number of individuals	Food items	Agriculture-related contaminants of concern		
	R	M	B	S	R/D			Se	B	DDE
Killdeer	✓	✓	✓	b	f	2,000	Terrestrial and aquatic invertebrates	L	L	H
Mountain plover		✓			f	1,500	Terrestrial invertebrates	--	--	H
Black-necked stilt	✓	✓	✓		f	100,000	Aquatic and terrestrial invertebrates	H	L	H
American avocet	✓	✓	r		m	100,000	Aquatic invertebrates	H	L	L
Greater yellowlegs		✓			m,f	≤60	Aquatic invertebrates, small fish	L	L	L
Lesser yellowlegs		✓			m,f	300	Aquatic and terrestrial invertebrates	L	L	L
Willet		✓			m,f	1,000	Aquatic invertebrates	L	L	--
Spotted sandpiper		✓			m	100	Aquatic invertebrates	L	L	--
Whimbrel		✓			m,f	10,000	Aquatic and terrestrial invertebrates	L	L	L
Long-billed curlew		✓			m,g	20,000	Terrestrial and aquatic invertebrates	L	--	H
Marlded godwit		✓		b		8,000	Aquatic and terrestrial invertebrates	L	L	--
Red know		✓		b		500	Aquatic invertebrates	L	L	--
Sanderling		✓		b		135	Aquatic invertebrates	L	L	--
Western sandpiper		✓		b		36,000	Aquatic invertebrates	L	L	--
Least sandpiper		✓		b		35,000	Aquatic invertebrates	L	L	--
Dunlin		✓		b		50	Aquatic invertebrates	L	L	--
Stilt sandpiper		✓		b		150	Aquatic invertebrates	L	L	--
Short-billed dowitcher		✓		b		3,400	Aquatic invertebrates	L	L	--

Authors: Is "g" correct? Not in headnote. Should it be "f"?

Table 27.--*Summary of agriculture-related contaminants of concern for birds subject to potential adverse effects, Salton Sea area* --Continued

Species	Status			Feeding habitat		Number of individuals	Food items	Agriculture-related contaminants of concern		
	R	M	B	S	R/D			Se	B	DDE
Long-billed dowitcher		✓				50,000	Aquatic invertebrates	L	L	--
Common snipe		✓			m	500	Aquatic invertebrates	L	L	L
Wilson's phalarope		✓		bo		10,000	Aquatic invertebrates	L	L	--
Red-necked phalarope		✓		bo		1,000	Aquatic invertebrates	L	L	--
Laughing gull	✓	✓	h	ob		[1]1,000	Fish, aquatic invertebrates	H	--	H
Bonapartes gull		✓		ob	f	[1]4,000	Terrestrial invertebrates, aquatic invertebrates, fish	L	L	H
Ring-billed gull		✓		ob	f	[1]100,000	Terrestrial invertebrates, fish	L	--	H
California gull	✓	✓		ob	f	[1]5,000	Terrestrial invertebrates	--	--	H
Herring gull		✓		ob	f	[1]5,000	Fish, invertebrates, amphibians	H	--	H
Yellow-footed gull		✓		ob		400	Small fish, aquatic invertebrates, dead mammals	H	--	H
Gull-billed tern	✓	✓	✓	b	f	300	Aquatic and terrestrial invertebrates	L	H	L
Caspian tern	✓	✓	h	ob		[1]500	Small fish	H	--	H
Common tern		✓		ob		[1]40	Small fish, aquatic invertebrates	H	L	H
Forster's tern	✓	✓	✓	ob		[1]5,000	Small fish	H	--	H
Black tern	✓	✓		b	f	[1]10,000	Invertebrates, small fish	L	L	H
Black skimmer	✓		✓	ob		600	Fish, aquatic invertebrates	H	--	H
Greater roadrunner	✓		✓		f	[1]500	Terrestrial insects, reptiles, small mammals	--	--	H

Table 27.--*Summary of agriculture-related contaminants of concern for birds subject to potential adverse effects, Salton Sea area* --Continued

Species	Status			Feeding habitat		Number of individuals	Food items	Agriculture-related contaminants of concern		
	R	M	B	S	R/D			Sc	B	DDE
Barn owl	✓		✓		f	[1]150	Small mammals, terrestrial insects	--	--	H
Burrowing owl	✓	✓	✓		f	[1]1,500	Terrestrial insects, small mammals	--	--	H
Belted kingfisher		✓			o	[1]250	Fish	H	--	H
Marsh wren	✓	✓	✓		m	[1]10,000	Aquatic and terrestrial insects	L	L	L
American pipit		✓			f	[1]50,000	Terrestrial and aquatic insects	L	--	H
Common yellowthroat	✓	✓	✓		m,r	[1]10,000	Aquatic and terrestrial insects	L	L	L

[1]Estimate by Salton Sea NWR staff, written commun., 1990; all other numbers are documented by count or survey.

Table 28.--Number of bird species (resident, migrant, or federally endangered) in the Salton Sea area that potentially are adversely affected by selenium, boron, or DDE.

[Number before diagonal is number of species potentially adversely affected by contaminant. Number after diagonal is total number of species in type category]

Type of bird	Drainwater contaminant		
	Se	B	DDE
Resident	35/42	23/42	34/42
Migrant	68/82	53/82	51/82
Endangered	3/4	1/4	4/4

Figure 1. Location of study area.

Figure 2. The Salton Sea. Looking east from south end of the sea toward the Chocolate Mountains.

Figure 3. The Salton Sea. Looking west across the north end of the sea toward Obsidian Butte.

Figure 4. Trophic relations among organisms of the Salton Sea.

Figure 5. Trophic relations among organisms of rivers and drains.

Figure 6. Numerous species of water birds utilizing the Salton Sea.

Figure 7. Dowitchers *(Limnodromus griseus)* feeding on invertebrates at the south end of Salton Sea.

Figure 8. Selenium cycle in aquatic ecosystems.

Figure 9. Subsurface-drainwater and surface-water sampling sites in the study area.

Figure 10. Biological sampling sites in the study area.

Figure 11. Regression plot of 1988 and 1986 selenium concentrations in subsurface-drainwater samples collected in the Imperial Valley.

Figure 12. Areal distribution of selenium concentration in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 13. Areal distribution of dissolved-solids concentration in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley, August 1988-August 1989.

Figure 15. Mean daily discharge in the Alamo River near Niland and the New River near Westmorland, water year 1989.

Figure 16. Contribution of trench flow to subsurface drainflow from a typical sump in the Imperial Valley.

Figure 17. Movement of water and layout of subsurface drains and soil-sampling sites in a typical field in the Imperial Valley.

Figure 18. Regression plot of hydrogen and oxygen isotopes and the meteoric water line for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 19. Regression plot of hydrogen isotopes and chloride for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 20. Regression plot of chloride and selenium for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 21. Selenium to chloride ratios in subsurface-drainwater samples collected at 119 sites in the Imperial Valley, May 1988.

Figure 22. Regression plot of hydrogen isotopes and $\log_{10}$ normalized chloride for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 23. Regression plot of $\log_{10}$ normalized chloride and boron for subsurface-drainwater samples collected during in the Imperial Valley, May 1988.

Figure 24. Regression plot of $\log_{10}$ normalized boron and dissolved solids for subsurface-drainwater samples collected in the Imperial Valley, May 1986. (Collected by California Regional Water Quality Control Board, Region VII.)

Figure 25. Boron to chloride ratios in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

Figure 26. Regression plot of hydrogen and oxygen isotopes and the meteoric water line for water samples from wells and lysimeters at three sites in the Imperial Valley.

Figure 27. Tritium concentration in water samples from lysimeters and wells at selected fields in the Imperial Valley.

Figure 28. Tritium concentration in water samples from the Colorado River, 1960-88.

Figure 29. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the northern site (near S-417) in the Imperial Valley.

Figure 30. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the middle site (near S-154) in the Imperial Valley.

Figure 31. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the southern site (near S-371) in the Imperial Valley.

Figure 32. Areal distribution of selenium in bottom sediments at the southern end of the Salton Sea.

Figure 33. Selenium bioaccumulation in transplanted Asiatic river clams, 1989-90.

Figure 34. Selenium exposure levels in livers of water birds and shorebirds utilizing the Salton Sea.

Figure 35. Selenium exposure levels in livers of water birds and shorebirds utilizing rivers and drains.

Figure 36. Cumulative distribution of selenium in black-necked stilt eggs from the Salton Sea, 1988-89.

Figure 37. Selenium pathway in the Salton Sea.

Figure 38. Selenium concentration in food-chain organisms of the Salton Sea.

Figure 39. Selenium pathway in rivers and drains.

Figure 40. Selenium concentration in food-chain organisms of rivers and drains.

Figure 41 Boron bioaccumulation in transplanted Asiatic river clams.

Figure 42. Boron concentration in livers of water birds and shorebirds from the Salton Sea area.

Figure 43. Cumulative distribution of boron in black-necked stilt eggs from the Salton Sea.

Figure 44. Boron pathway in the Salton Sea.

Figure 45. Boron pathway in rivers and drains.

Figure 46. Boron concentration in food-chain organisms of the Salton Sea, 1986-90.

Figure 47. Boron concentration in food-chain organisms of rivers and drains.

Figure 48. DDT concentration in transplanted Asiatic river clams.

Figure 49. Total DDT concentration for three species of fish from the Salton Sea.

Figure 50. DDT concentrations in black-necked stilt eggs and reproductive-impairment thresholds for various bird species.

Figure 51. Correlation between DDE concentration and eggshell thickness for black-necked stilts from the Salton Sea, 1988-89.

Figure 52. p,p'-DDE concentration in black-necked stilt eggs from selected nesting populations in the Salton Sea area, 1988-19.

Figure 53. DDE concentration in black-necked stilt eggs from selected nesting populations in the Salton Sea area, 1989.

Figure 54. DDE pathway in the Salton Sea.

Figure 55. DDE pathway in rivers and drains.

Figure 56. Total DDT concentration in food-chain organisms of the Salton Sea.

Figure 57. p,p'-DDE concentration in food-chain organisms of the Salton Sea.

Figure 58. Total DDT concentration if food-chain organisms of rivers and drains.

Figure 59. p,p'-DDE concentration in food-chain organisms of rivers and drains.

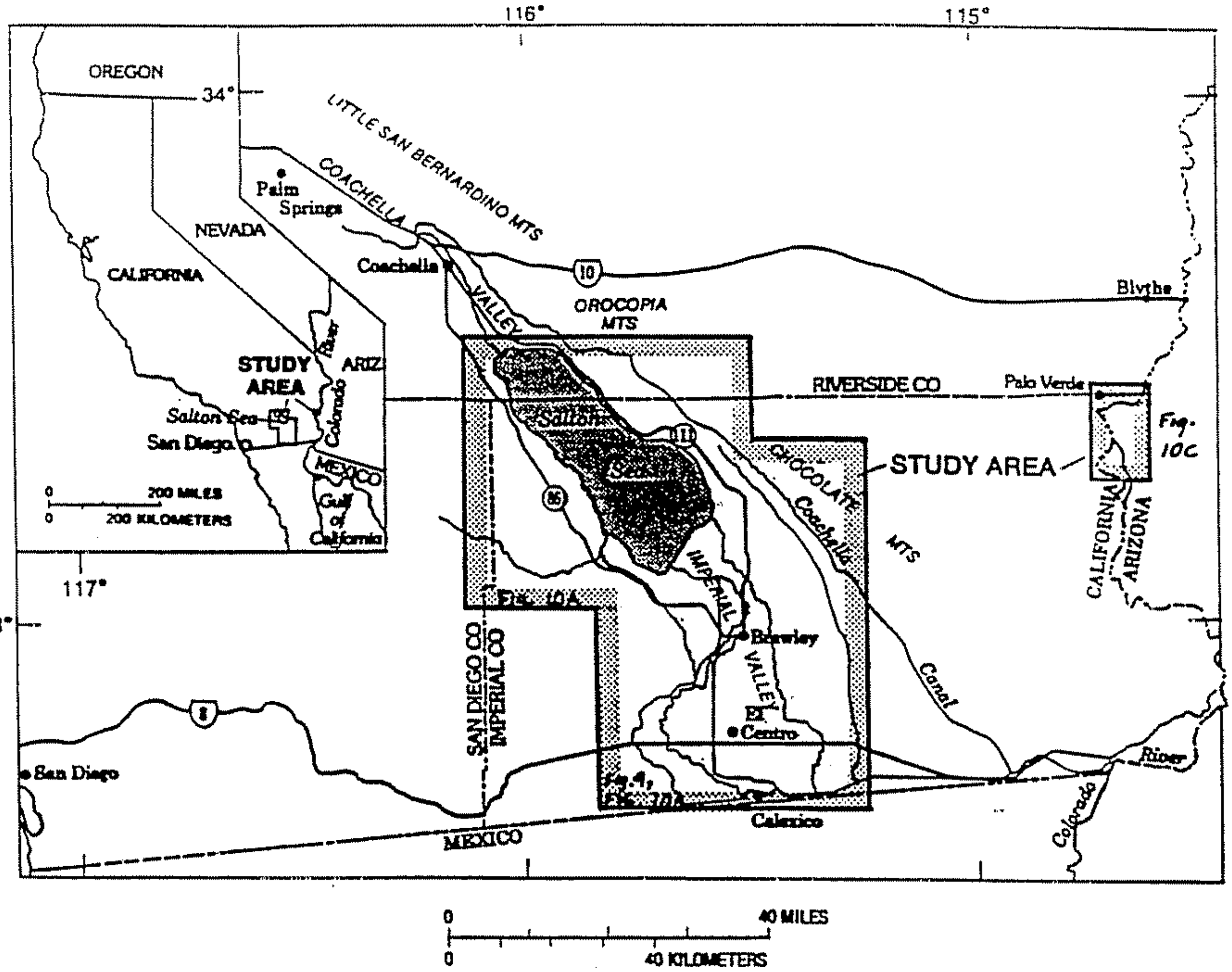


Figure 1. Location of study area.

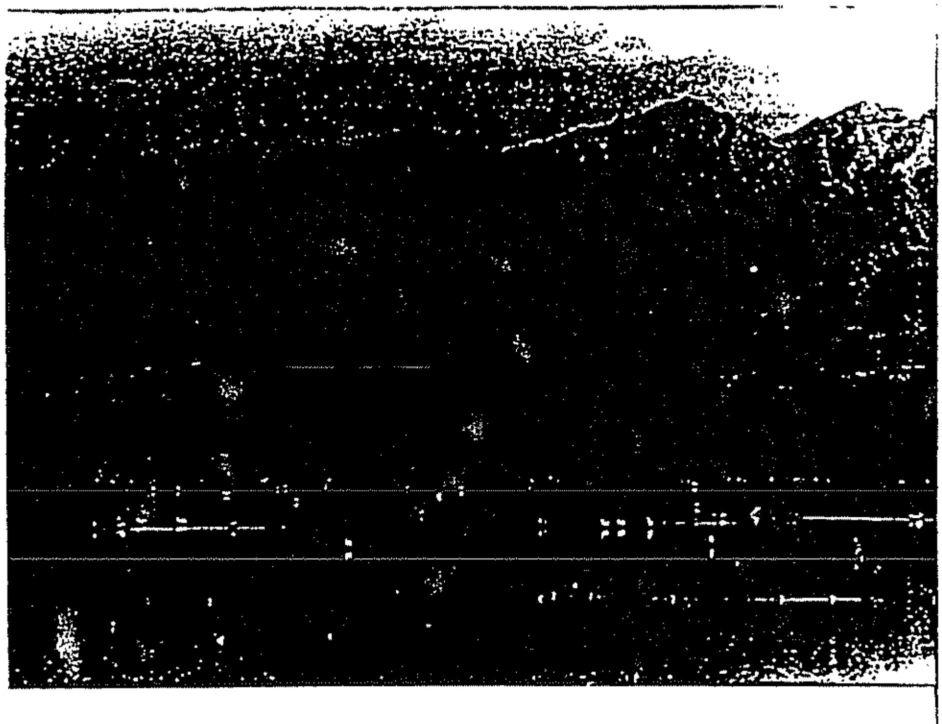


Figure 2. The Salton Sea. Looking east from south end of the sea toward the Chocolate Mountains.

Figure 3. The Salton Sea. Looking west across the north end of the sea toward Obsidian Butte.

Figure 4 Folded

Figure 5 Folded

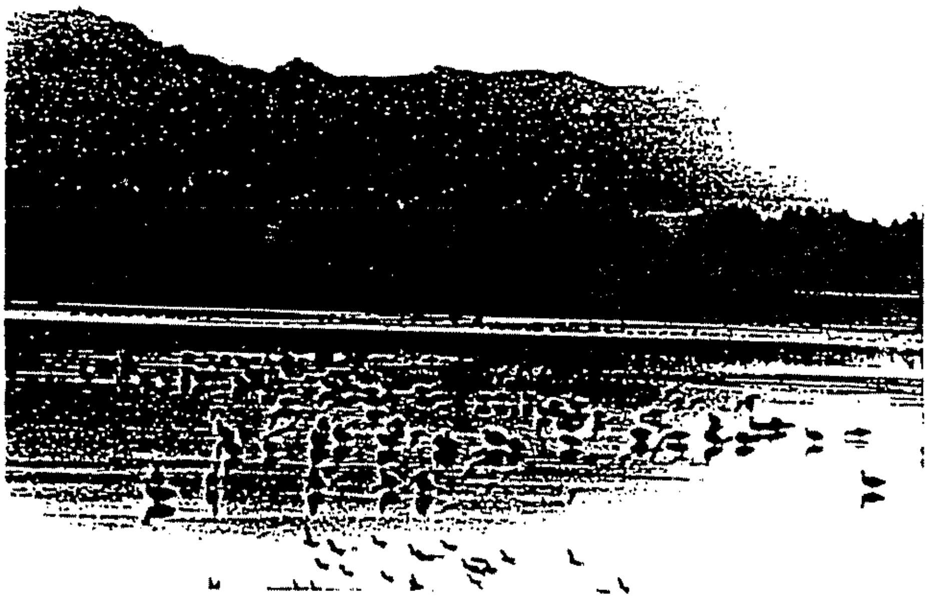


Figure 6. Numerous species of water birds utilizing the Salton Sea.

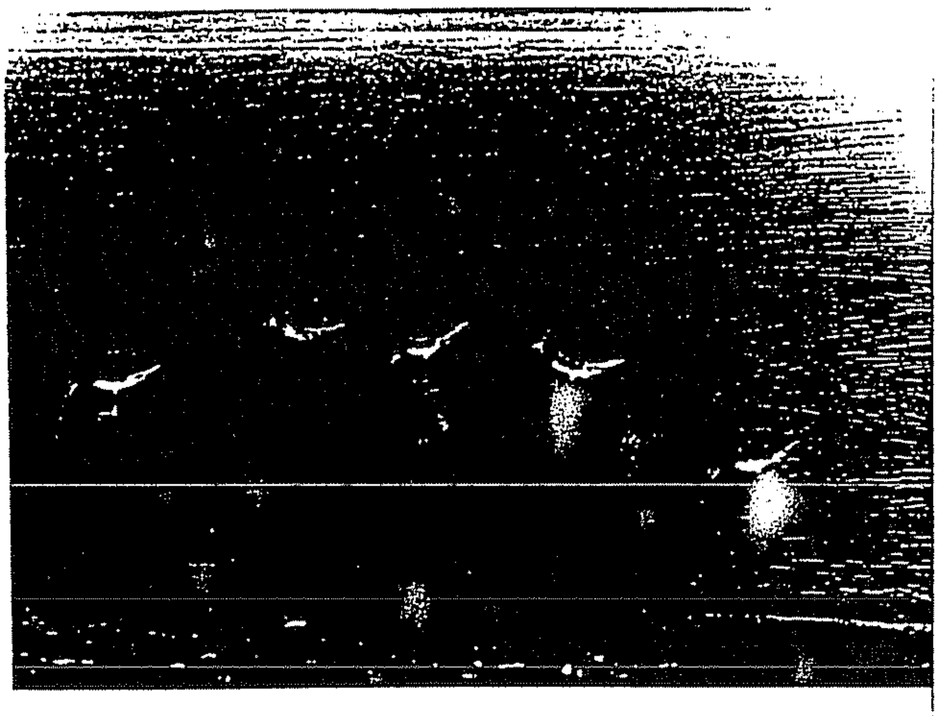


Figure 7. Dowitchers *(Limnodromus griseus)* feeding on invertebrates at the south end of Salton Sea.

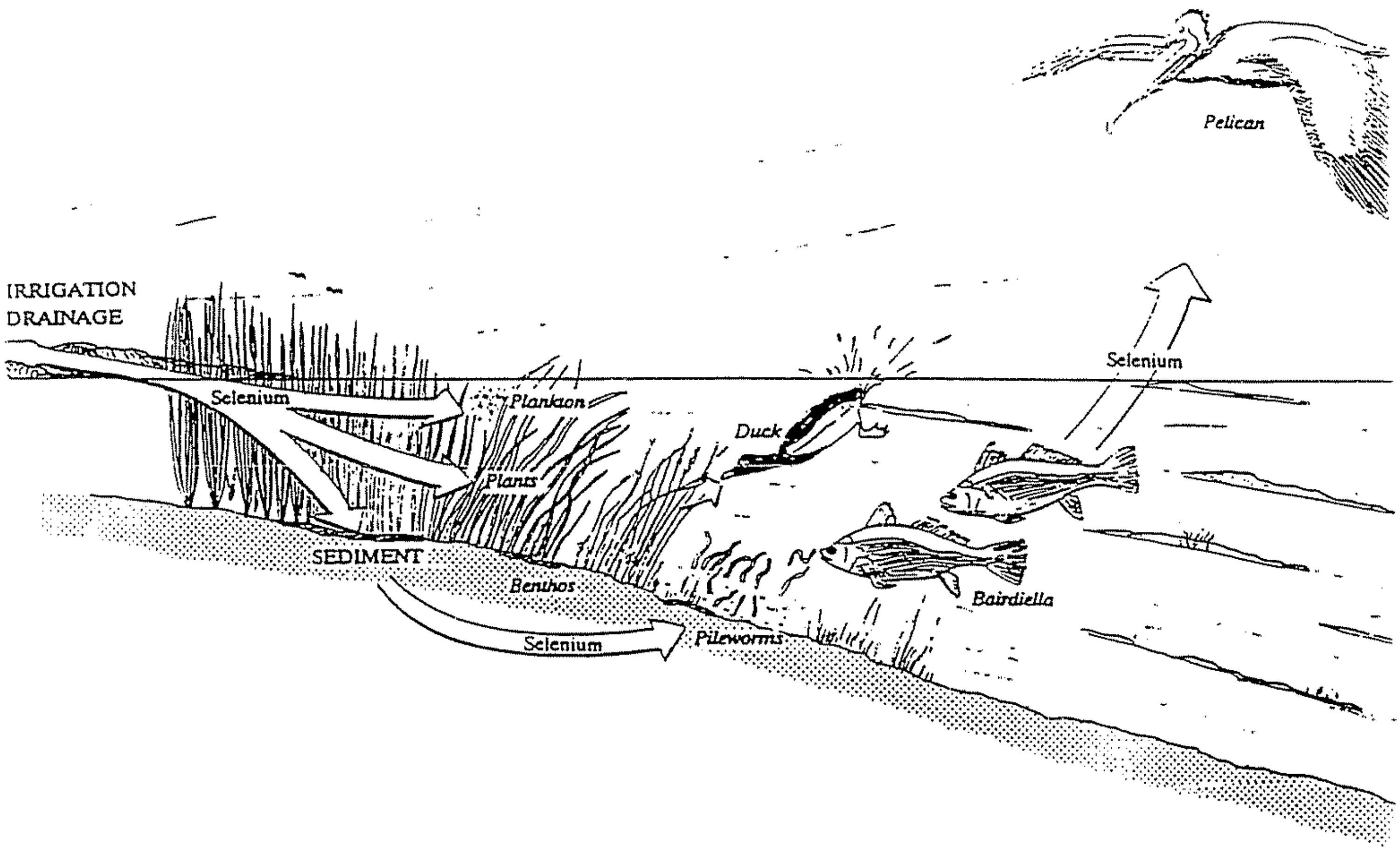


Figure 8. Selenium cycle in aquatic ecosystems.

EXPLANATION

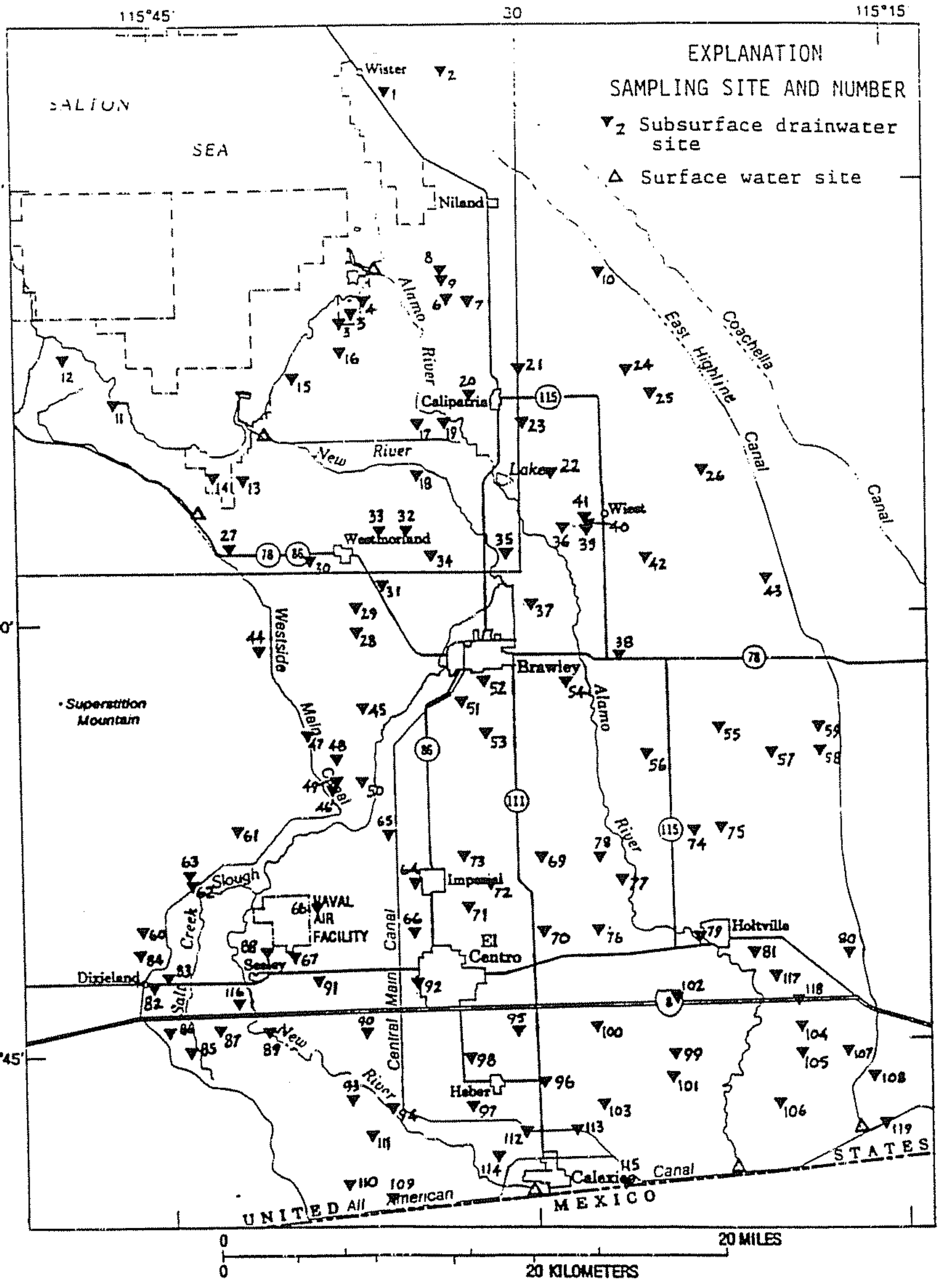
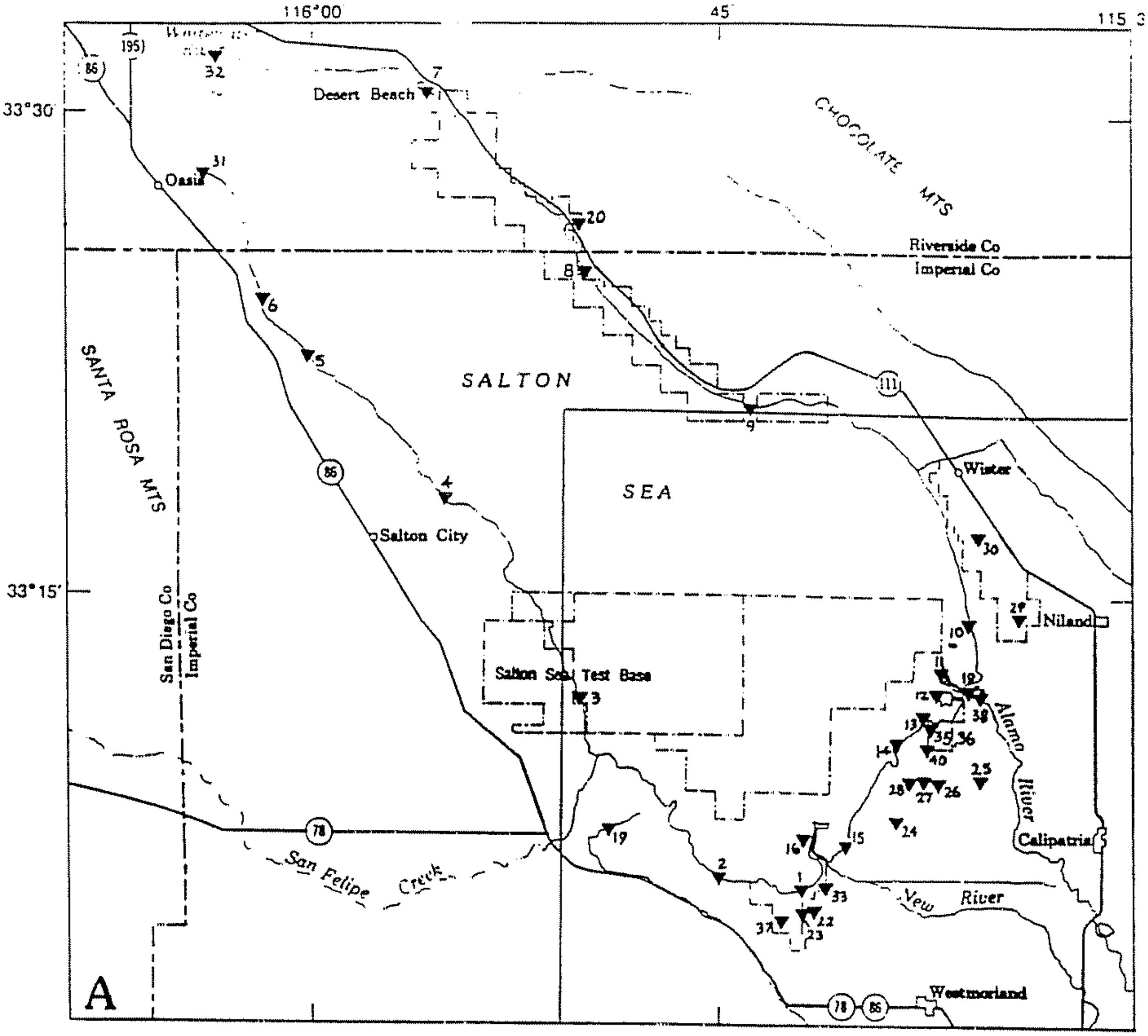


Figure 9. Subsurface-drainwater and surface-water sampling sites in the study area.



EXPLANATION

2 ▼ BIOLOGICAL SAMPLING SITE AND NUMBER

Figure 10. Biological sampling sites. Area of maps is shown in figure 1.

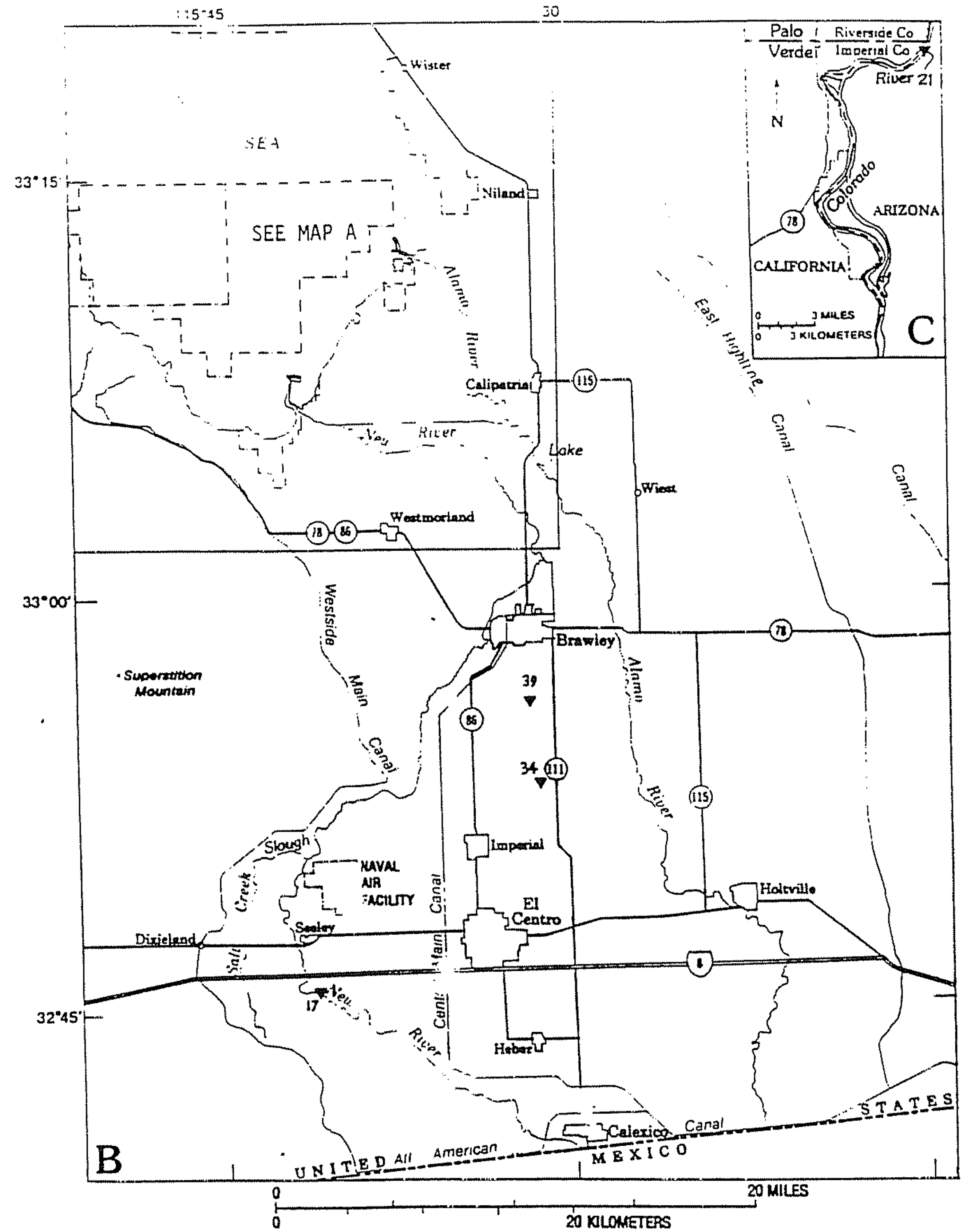


Figure 10. Biological sampling sites--Continued.

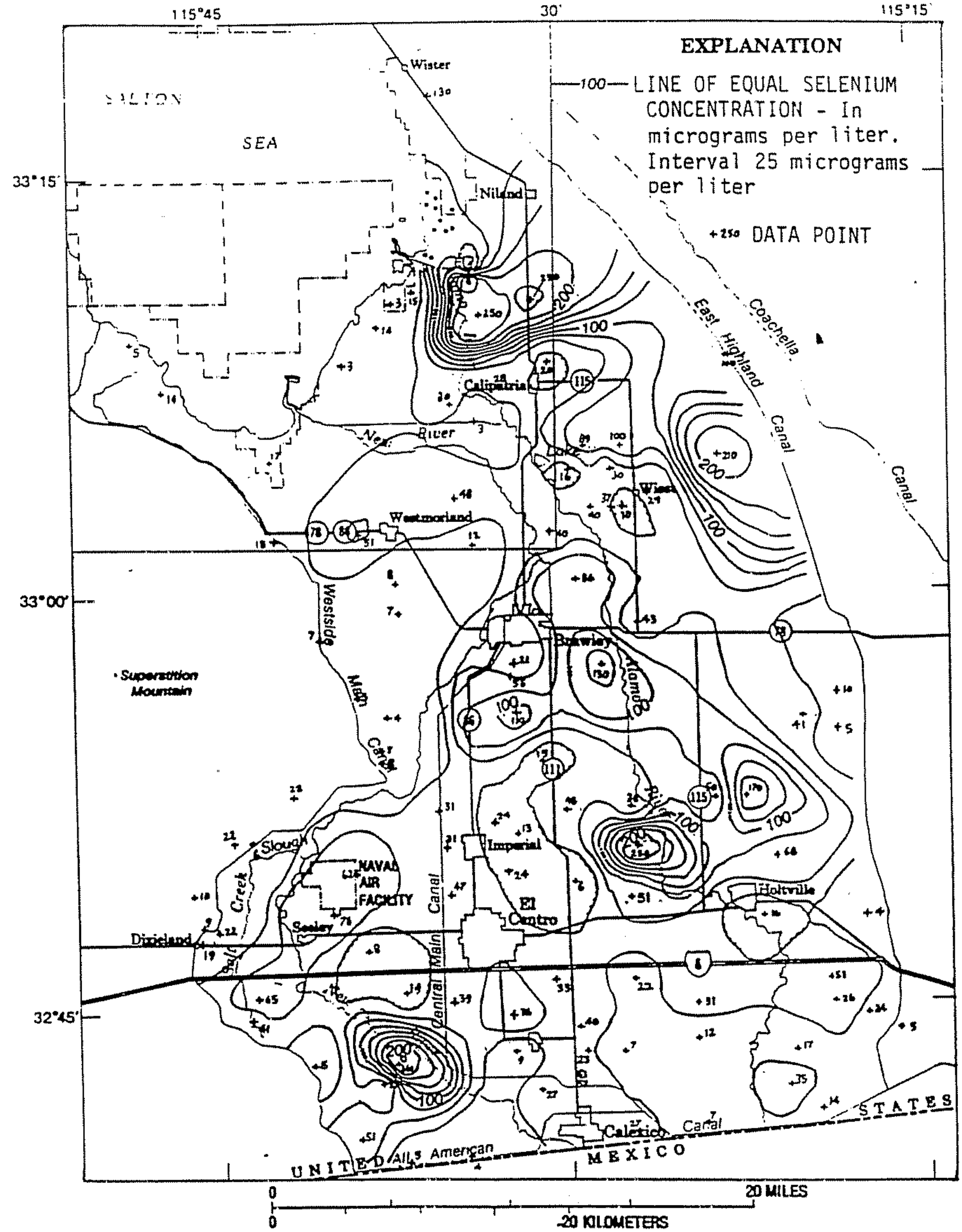


Figure 12. Areal distribution of selenium concentration in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

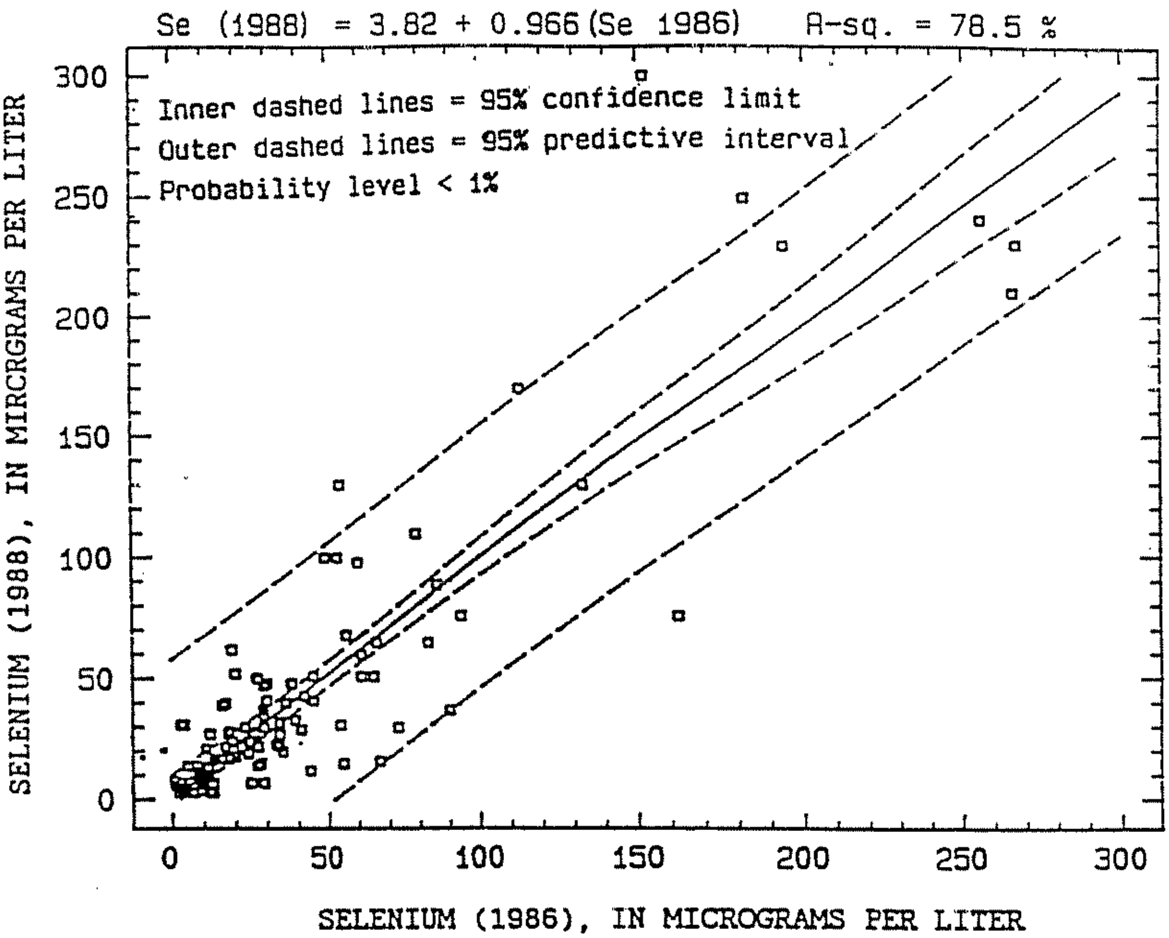


Figure 11. Regression plot of 1988 and 1986 selenium concentrations in subsurface-drainwater samples collected in the Imperial Valley.

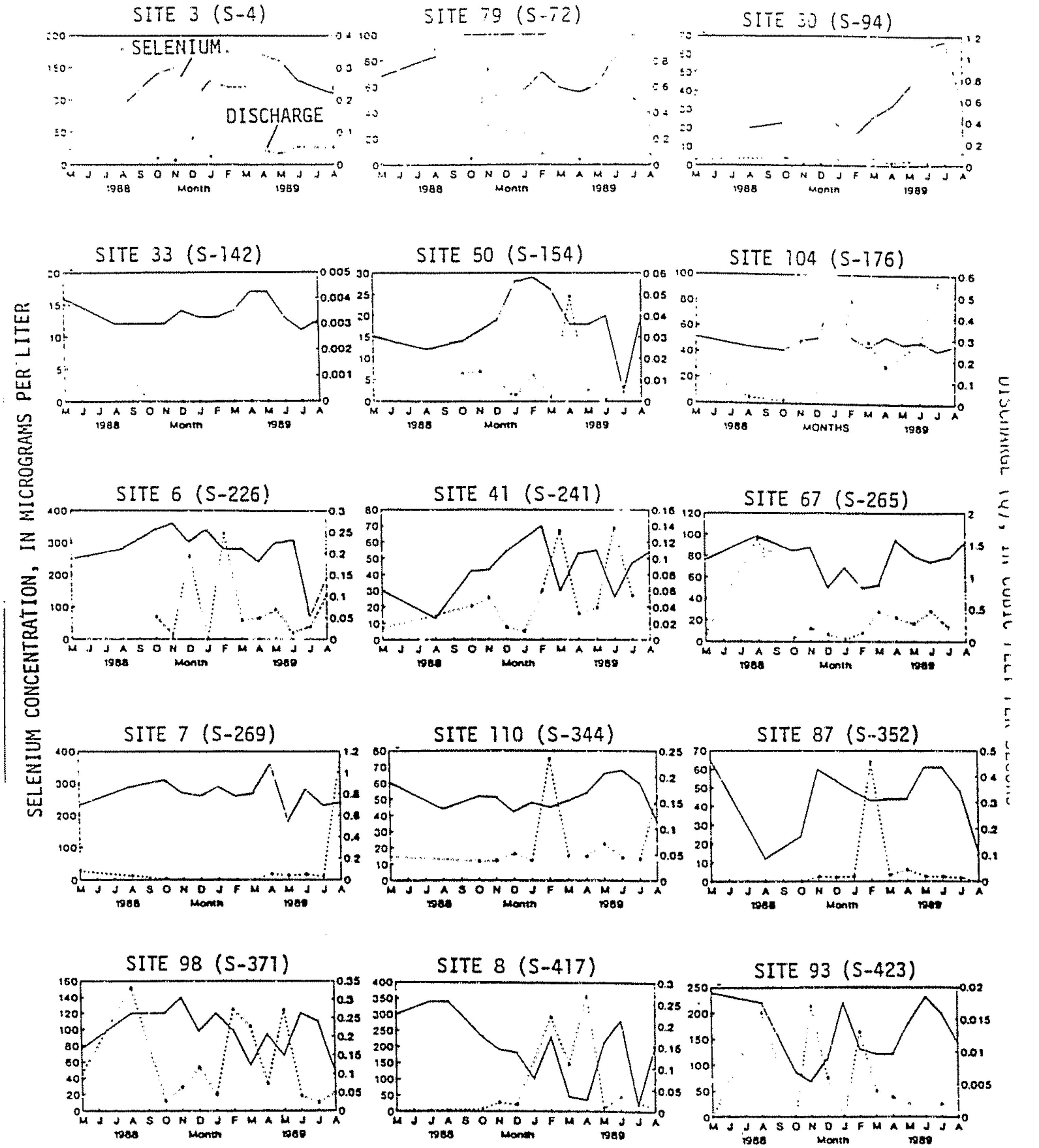


Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley, May 1988 and August 1988-August 1989. (Site number with sump number in parentheses, is given above each graph. Location of sites is shown in figure 6.)

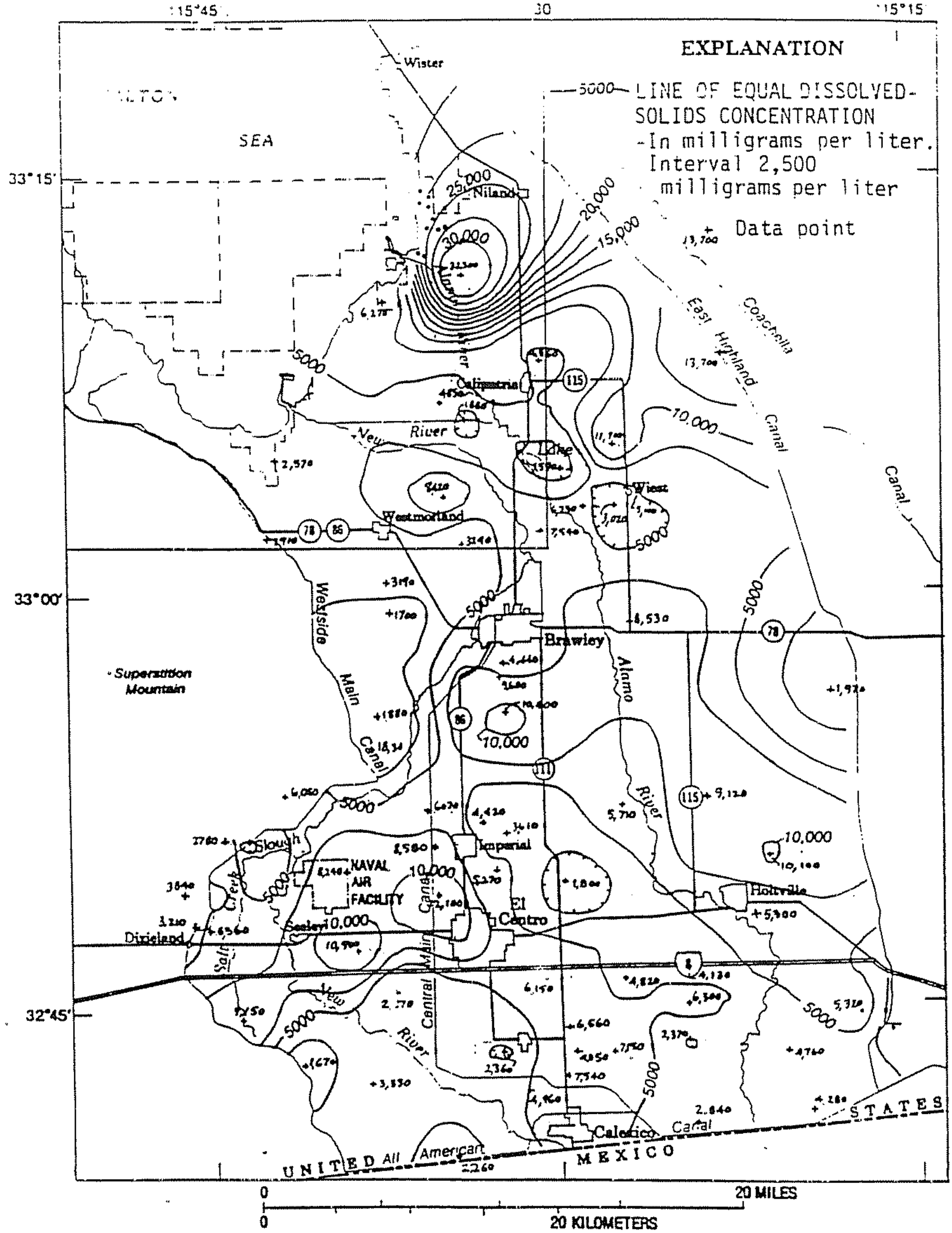


Figure 13. Areal distribution of dissolved-solids concentration in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

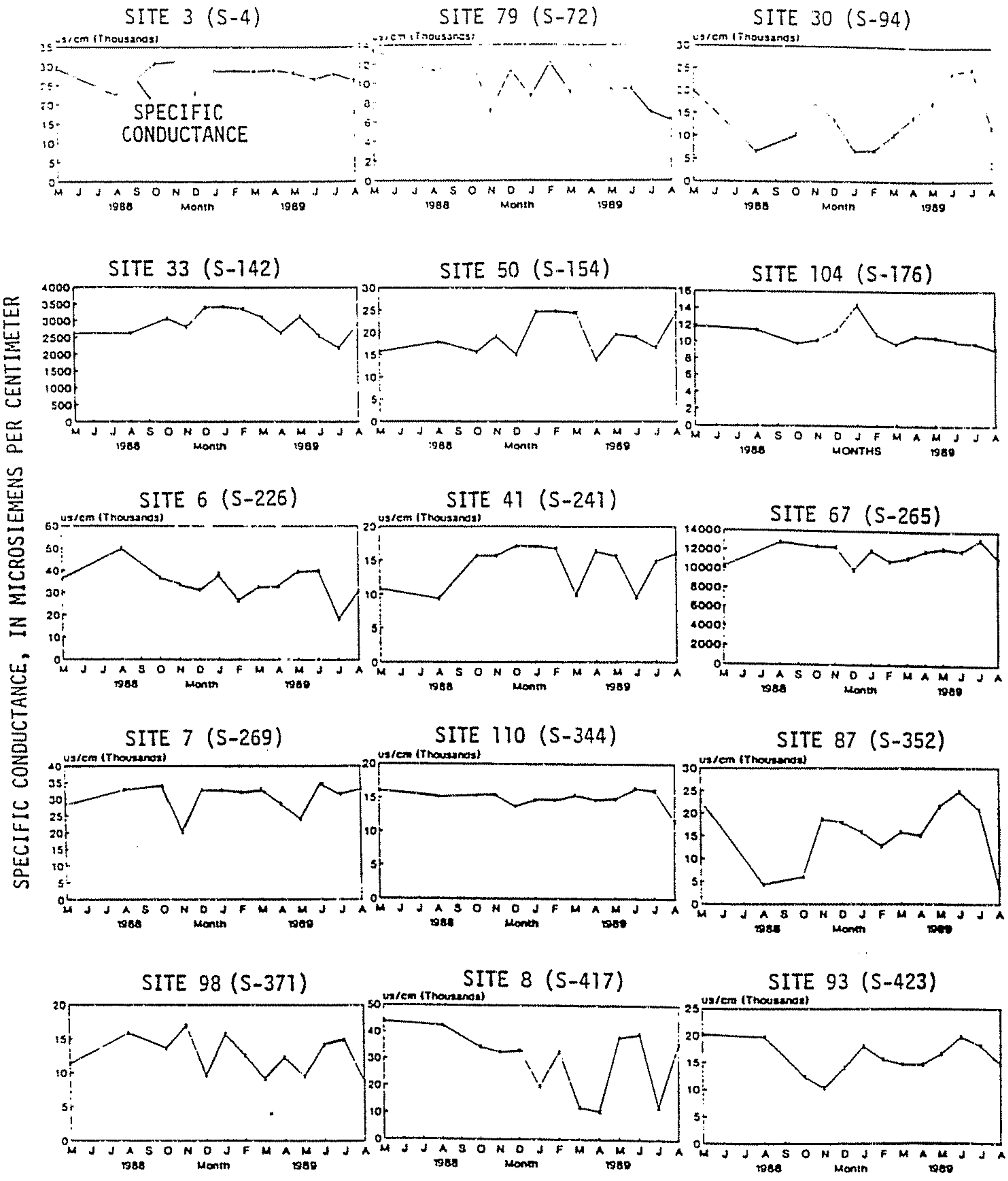


Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley,—Contin

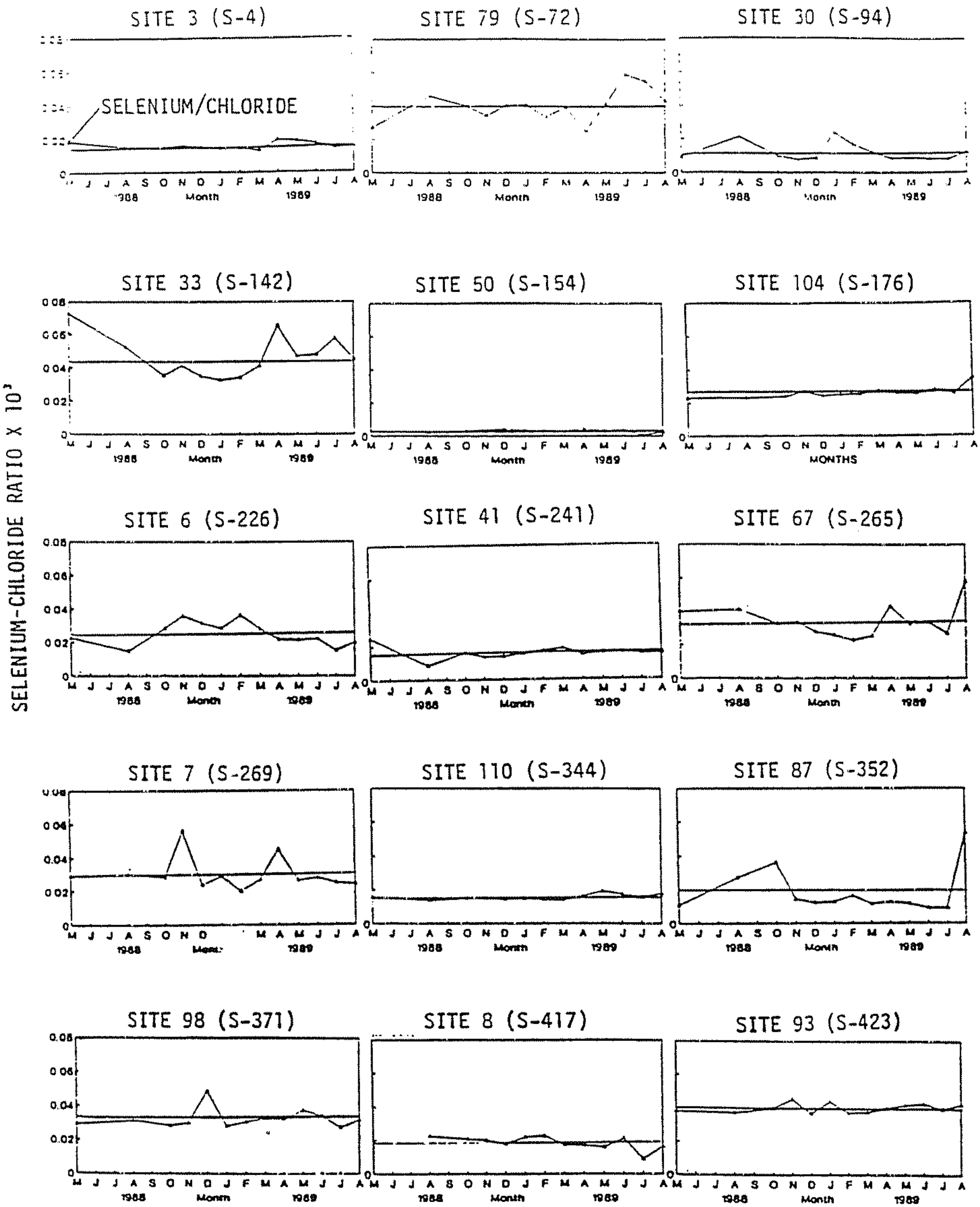


Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley,--Contin

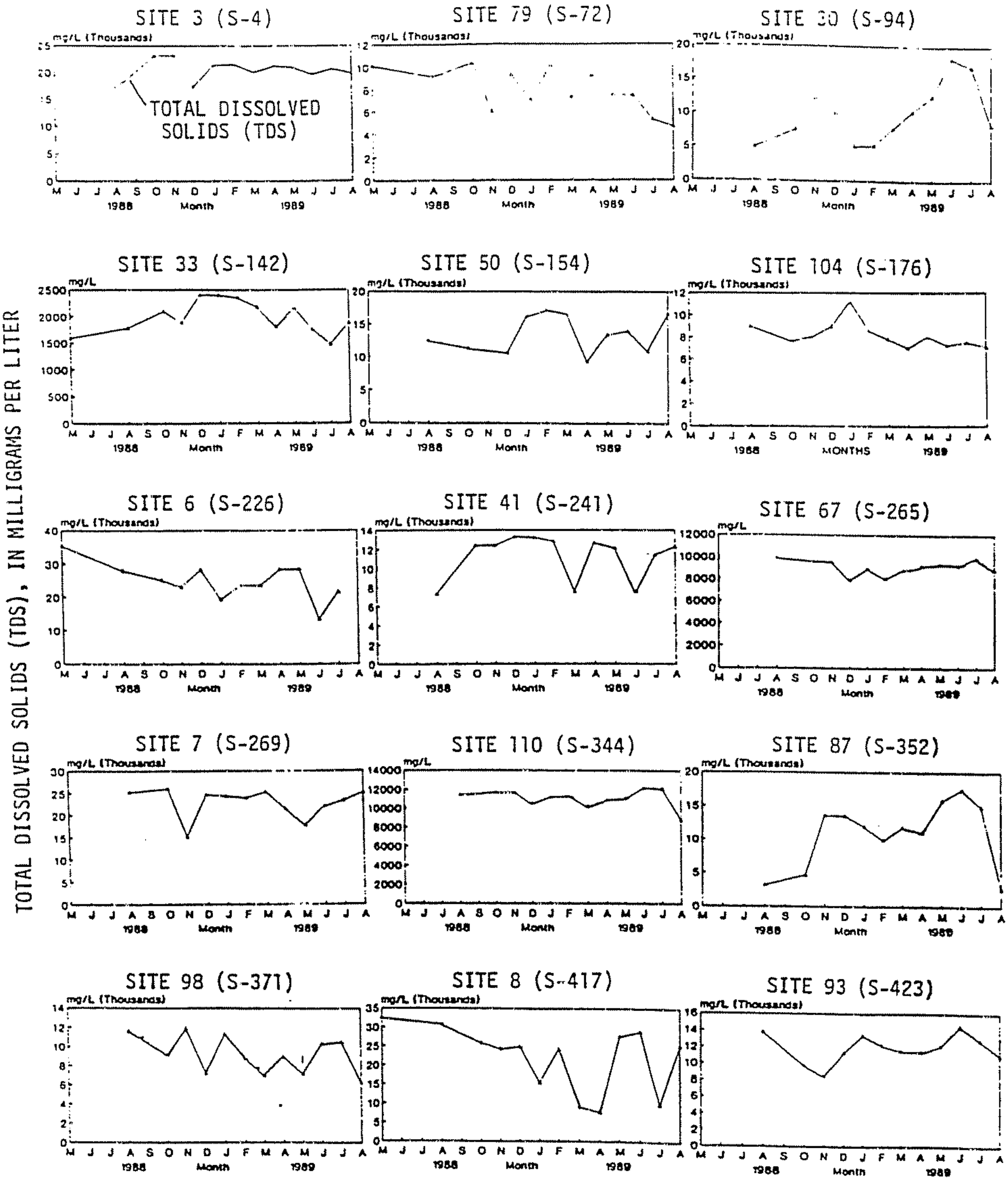


Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley.--Continued

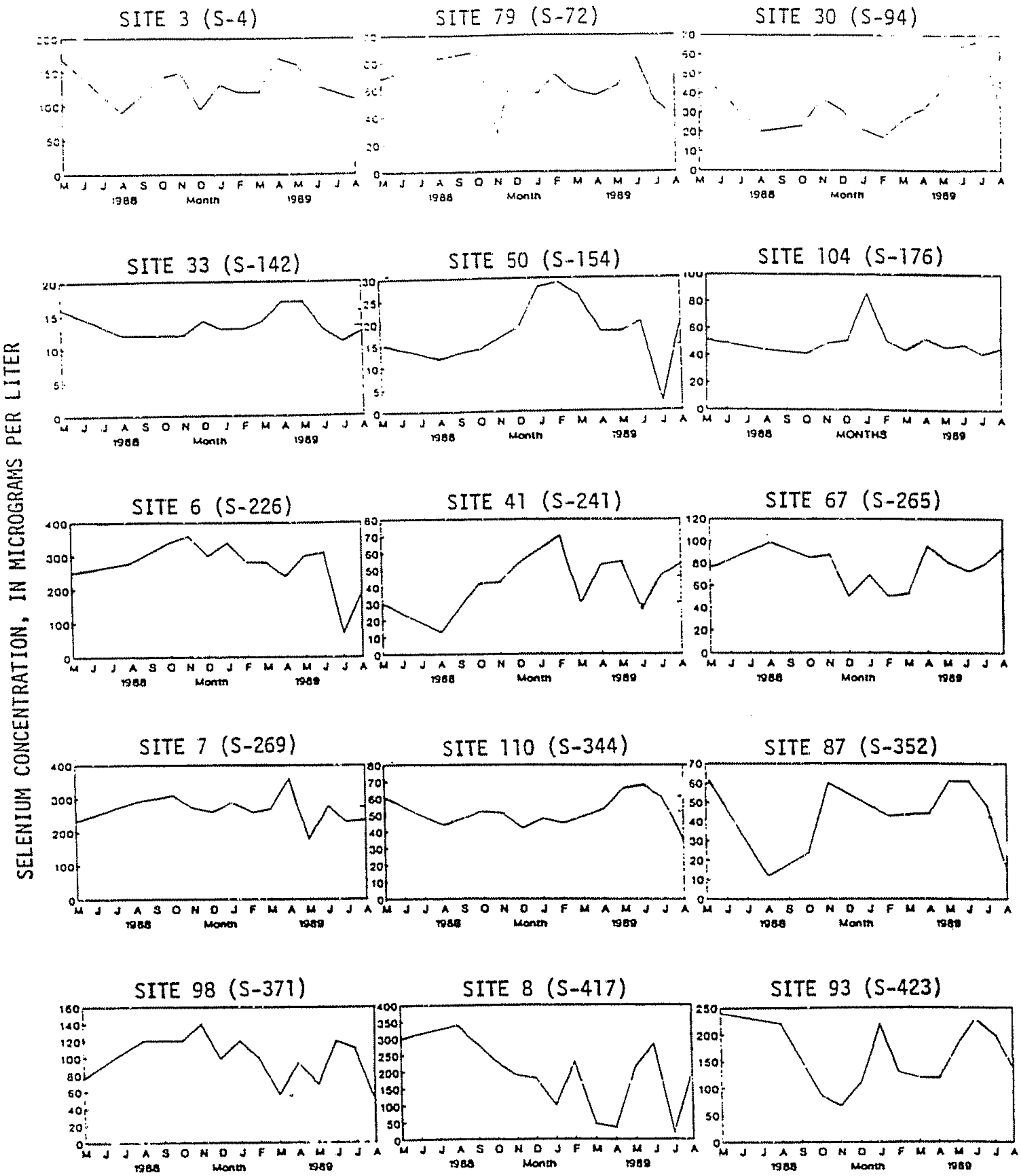
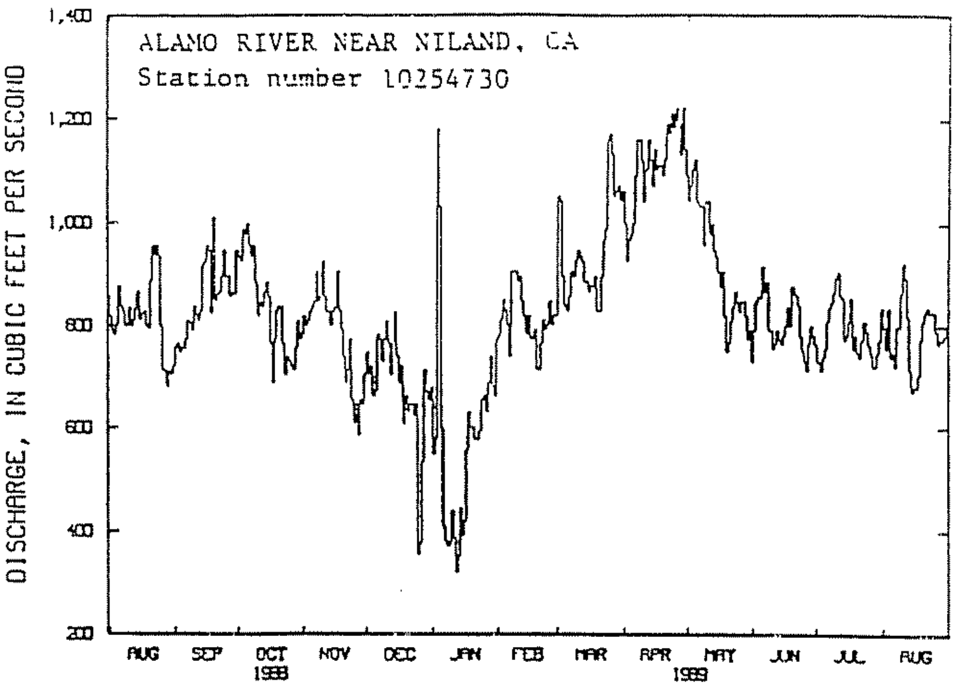


Figure 14. Temporal variation in concentrations of selected constituents in subsurface-drainwater samples collected from 15 fields in the Imperial Valley,--Conti



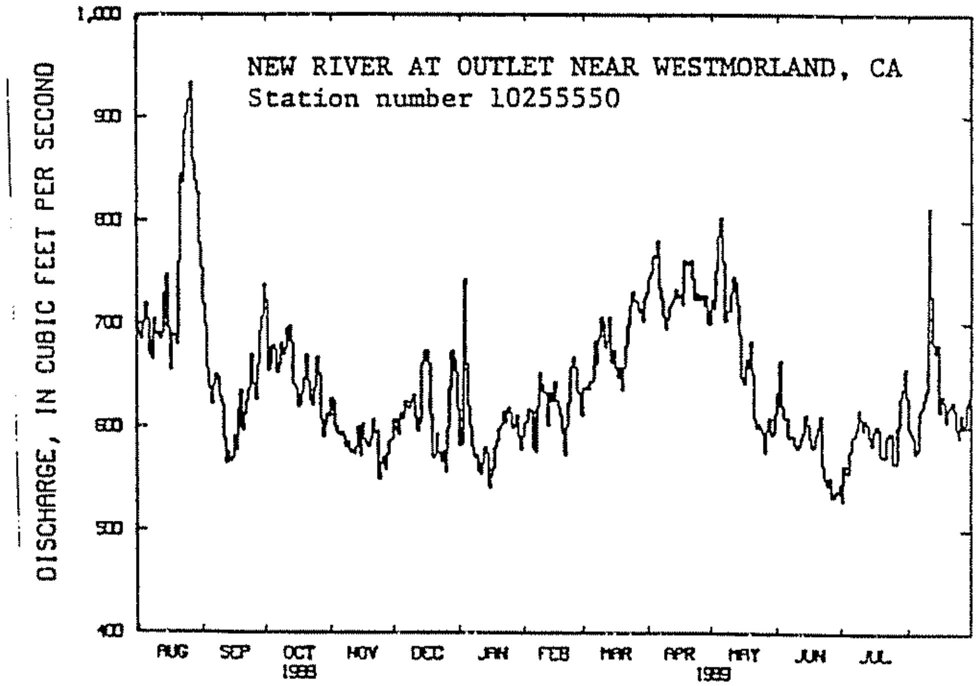


Figure 15. Mean daily discharge in the Alamo River near Niland and the New River near Westmorland, water year 1989.

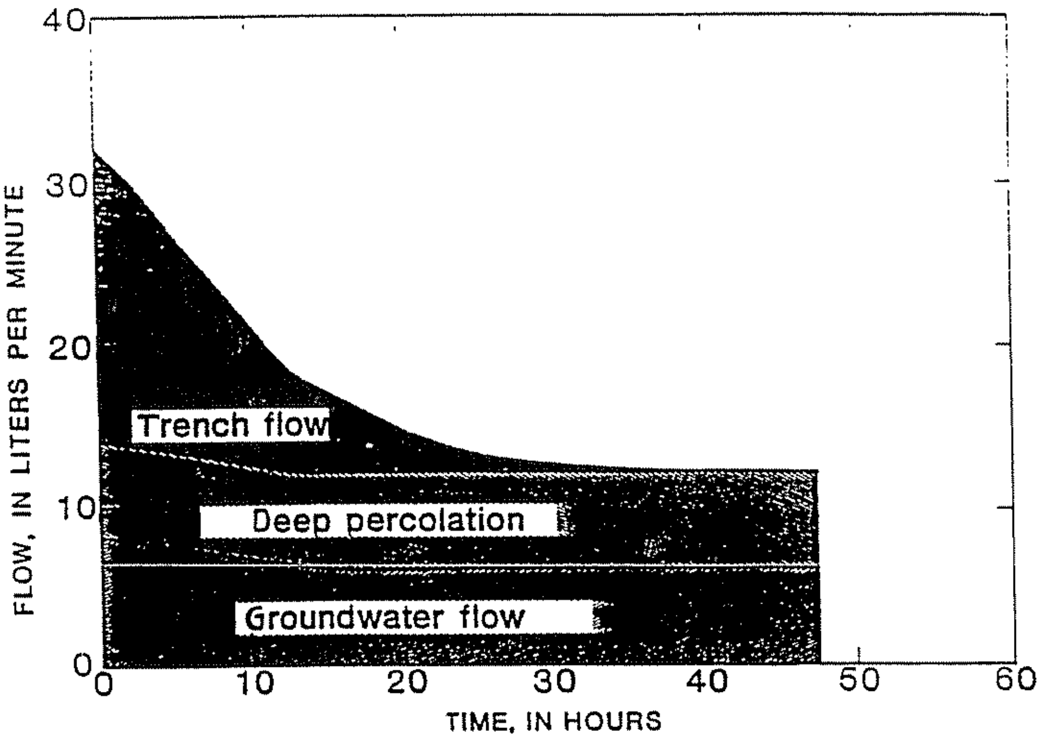
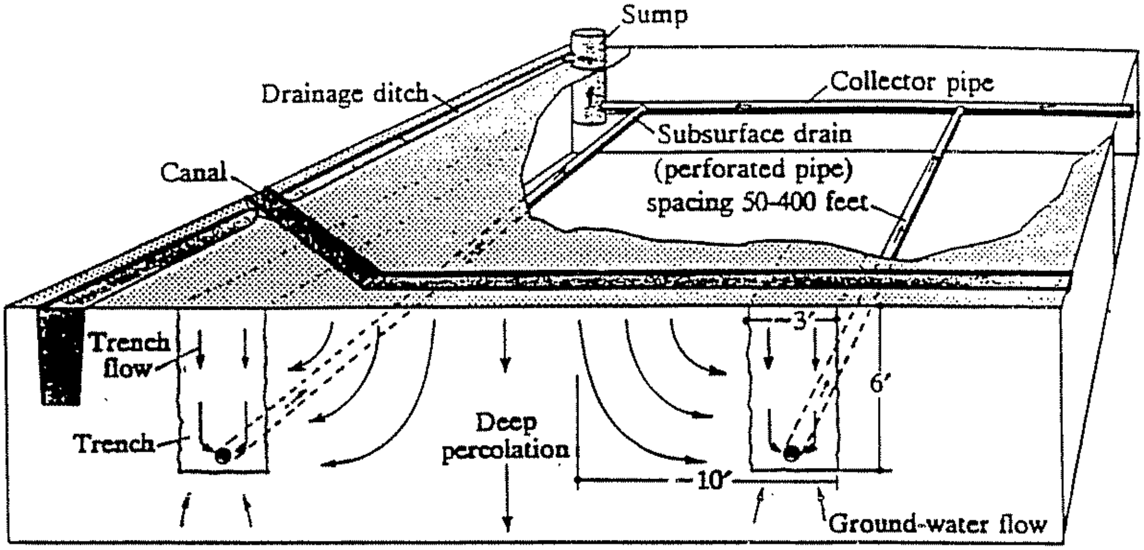
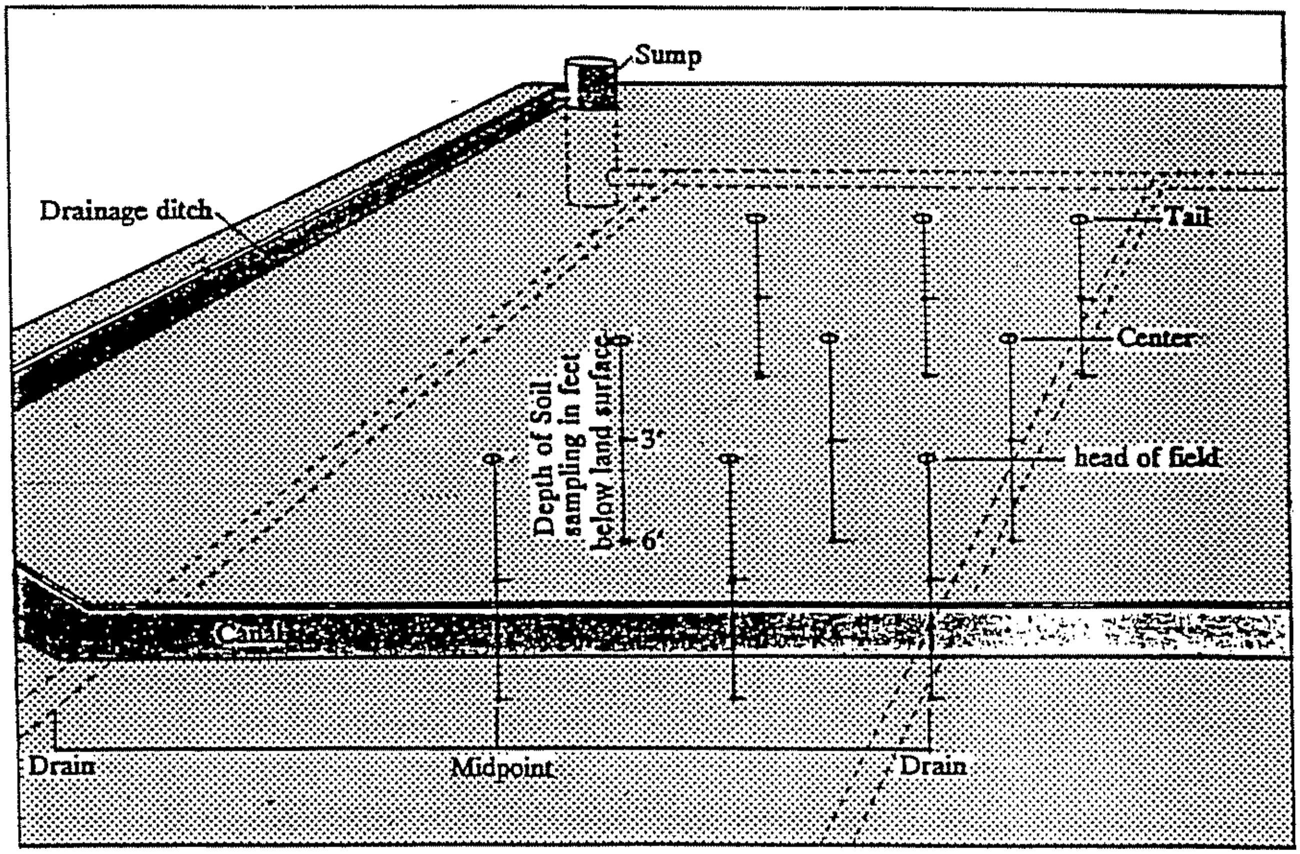


Figure 16. Contribution of trench flow to subsurface drainflow from a typical sump in the Imperial Valley.



A. Movement of water and layout of subsurface drains

Modified from Tod and Grismer, 1988



B. Soil-sampling configuration

Figure 17. Movement of water and layout of subsurface drains and soil-sampling sites in a typical field in the Imperial Valley.

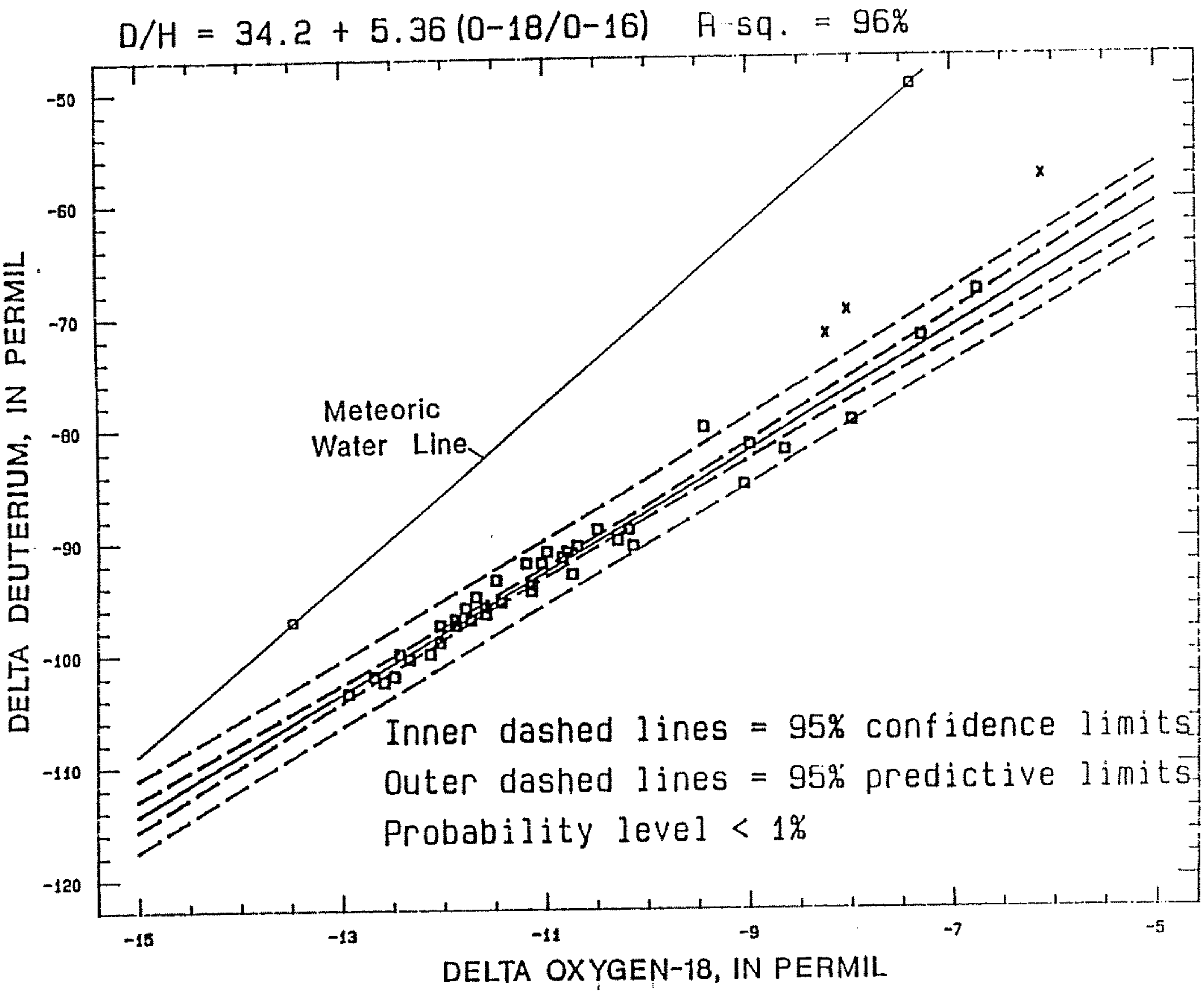


Figure 18. Regression plot of hydrogen and oxygen isotopes and the meteoric water line for

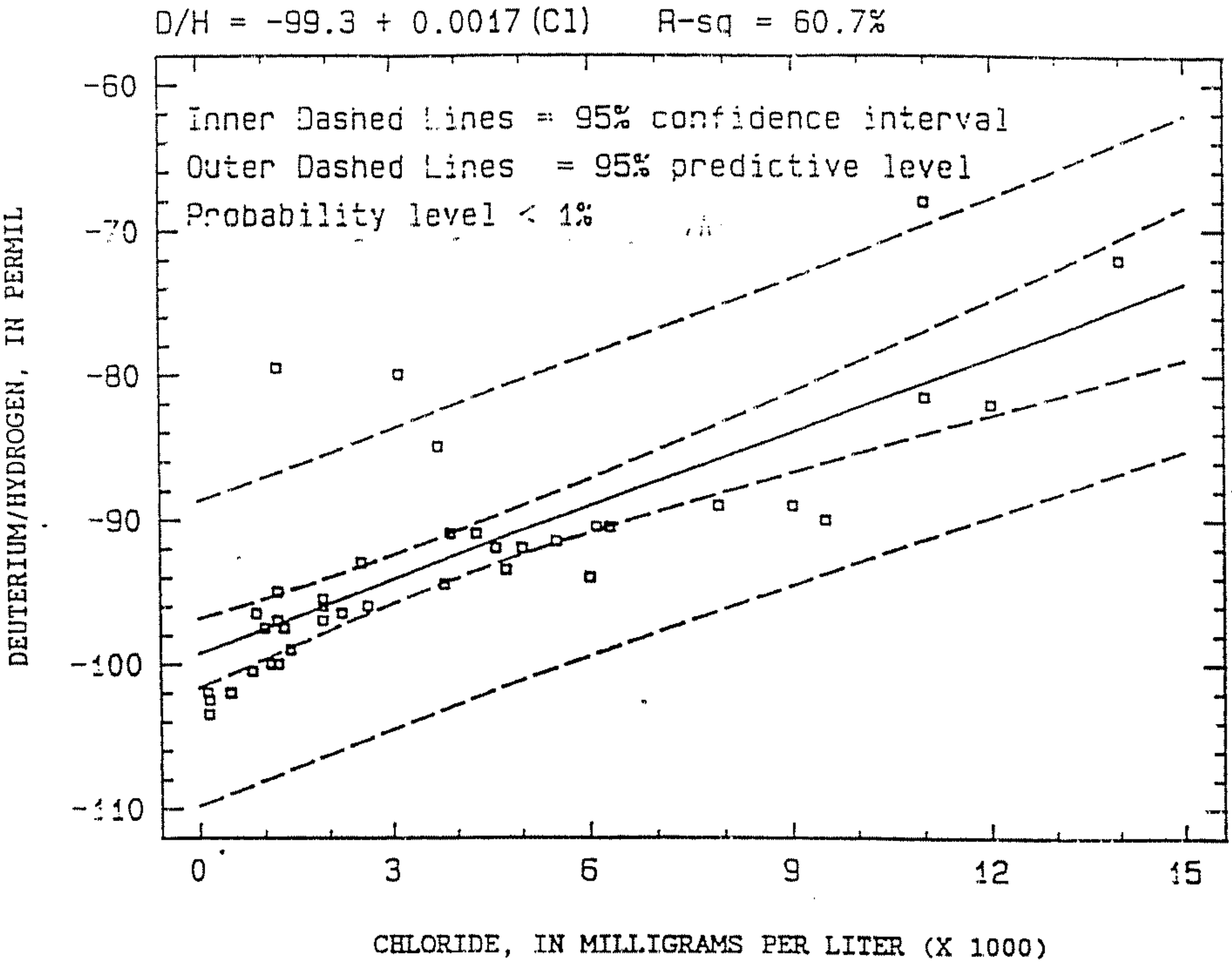


Figure 19. Regression plot of hydrogen isotopes and chloride for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

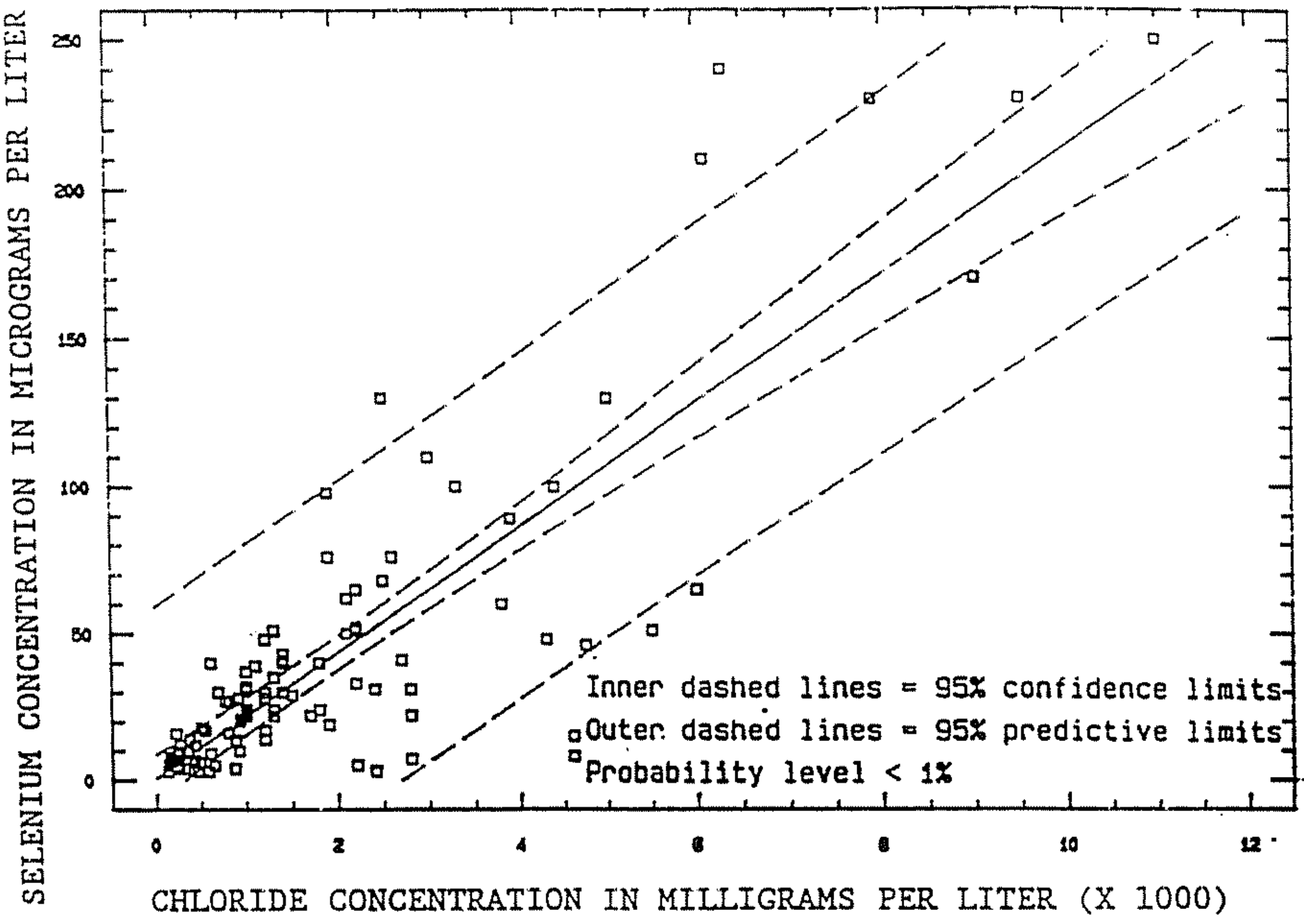


Figure 20. Regression plot of chloride and selenium for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

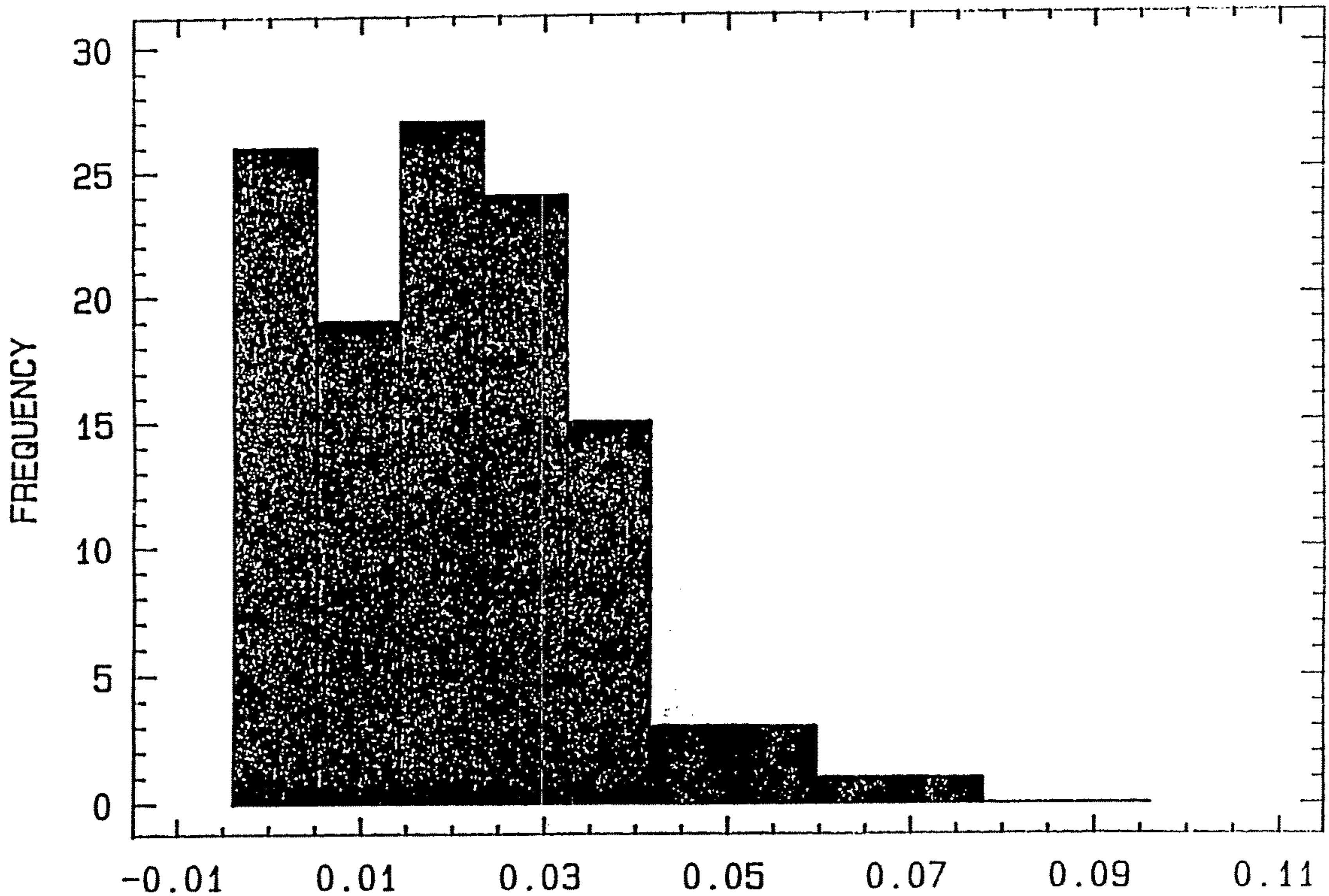


Figure 21. Selenium to chloride ratios in subsurface-drainwater samples collected at 119 sites in the Imperial Valley, May 1988.

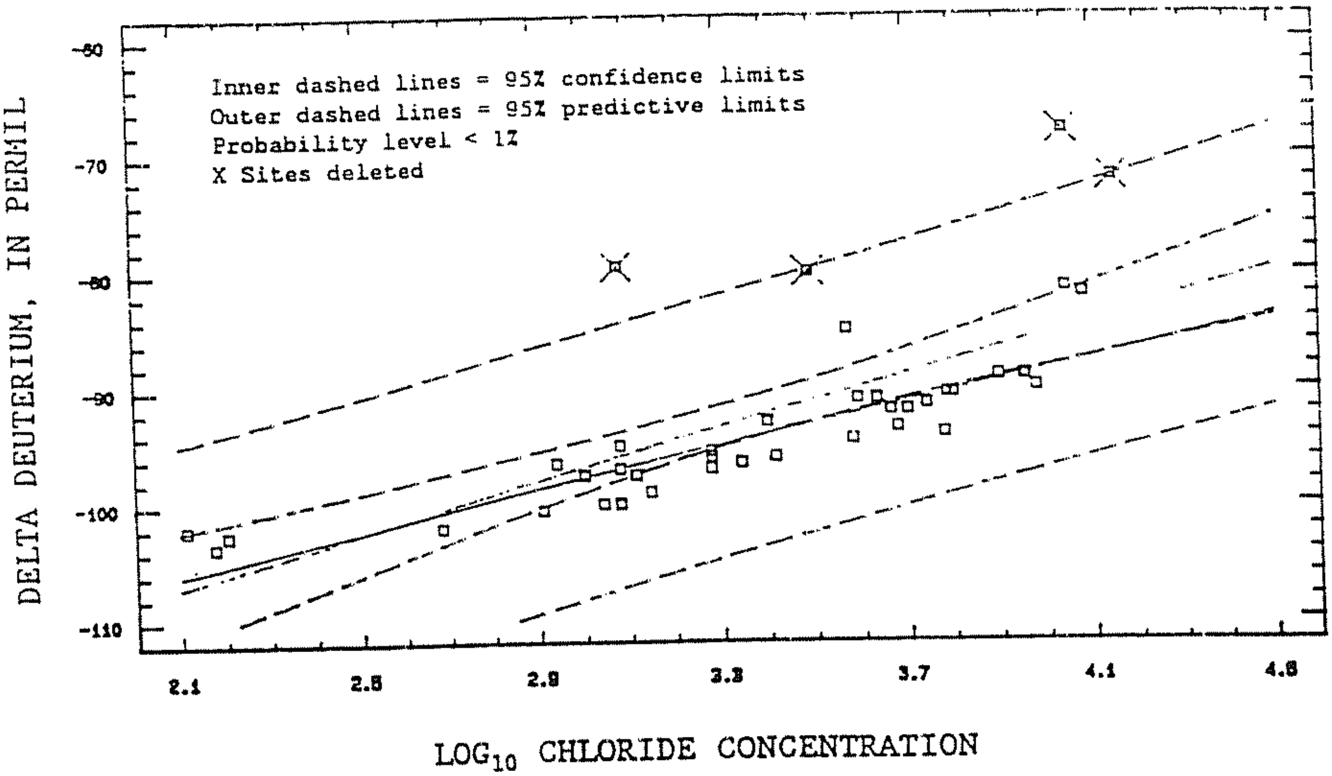


Figure 22. **Regression plot of hydrogen isotopes and $\log_{10}$ normalized chloride for subsurface-drainwater samples collected in the Imperial Valley,** May 1988.

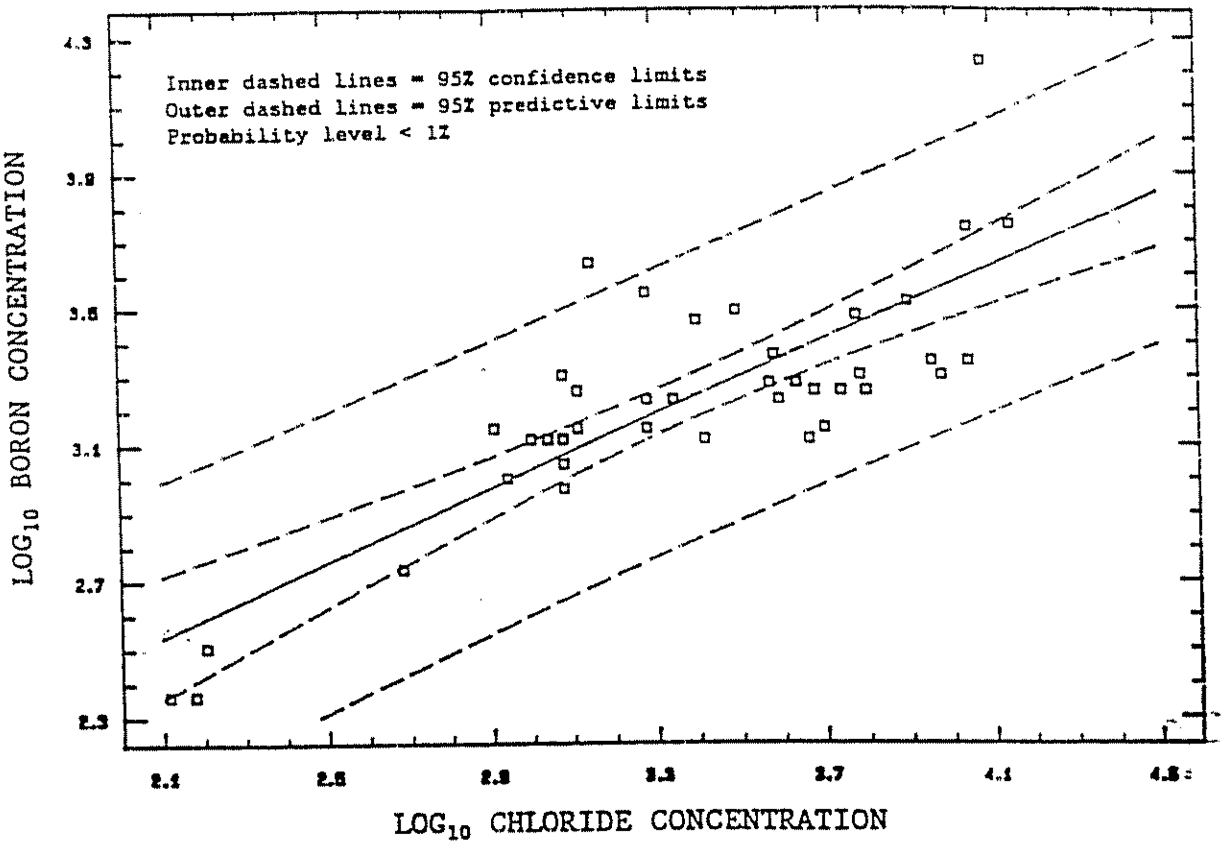


Figure 23. Regression plot of $\log_{10}$ normalized chloride and boron for subsurface-drainwater samples collected in the Imperial Valley, May 1988.

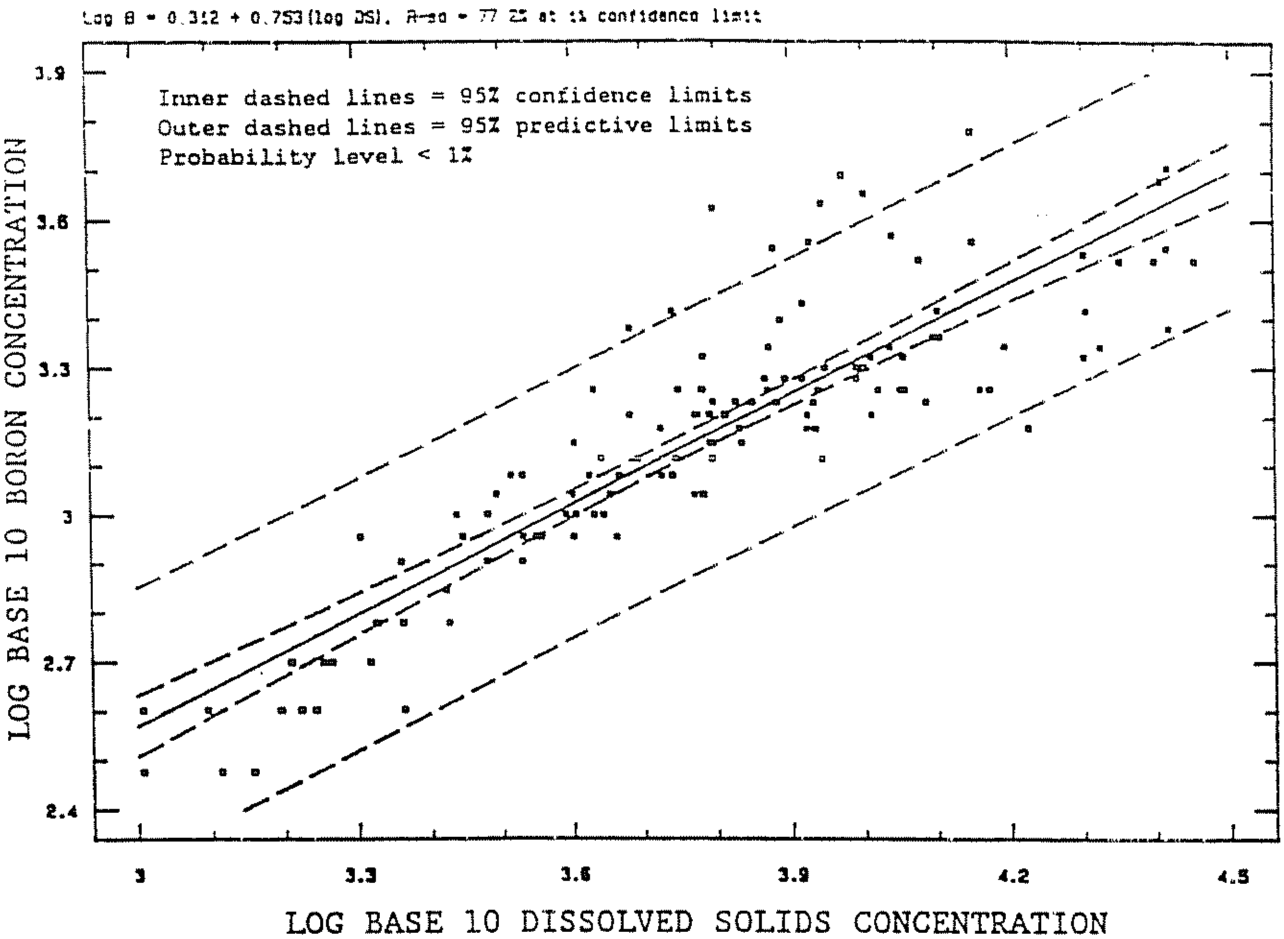


Figure 24. Regression plot of $\log_{10}$ normalized boron and dissolved solids for subsurface-drainwater samples collected in the Imperial Valley, May 1986. (Collected by California Regional Water Quality Control Board, Region VII.)

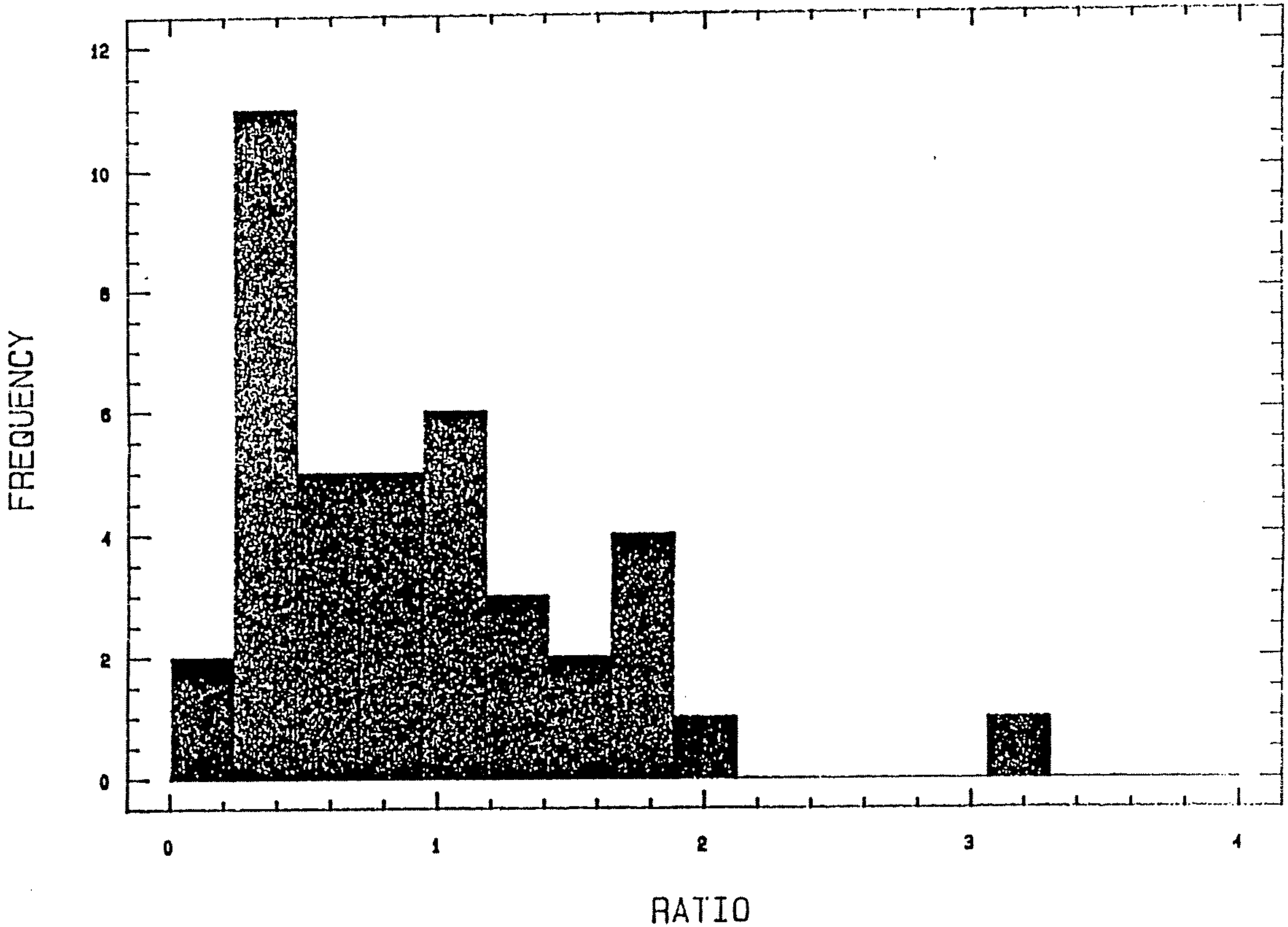


Figure 25. Boron to chloride ratios in subsurface-drainwater samples collected in the Imperial Valley, May 1988.

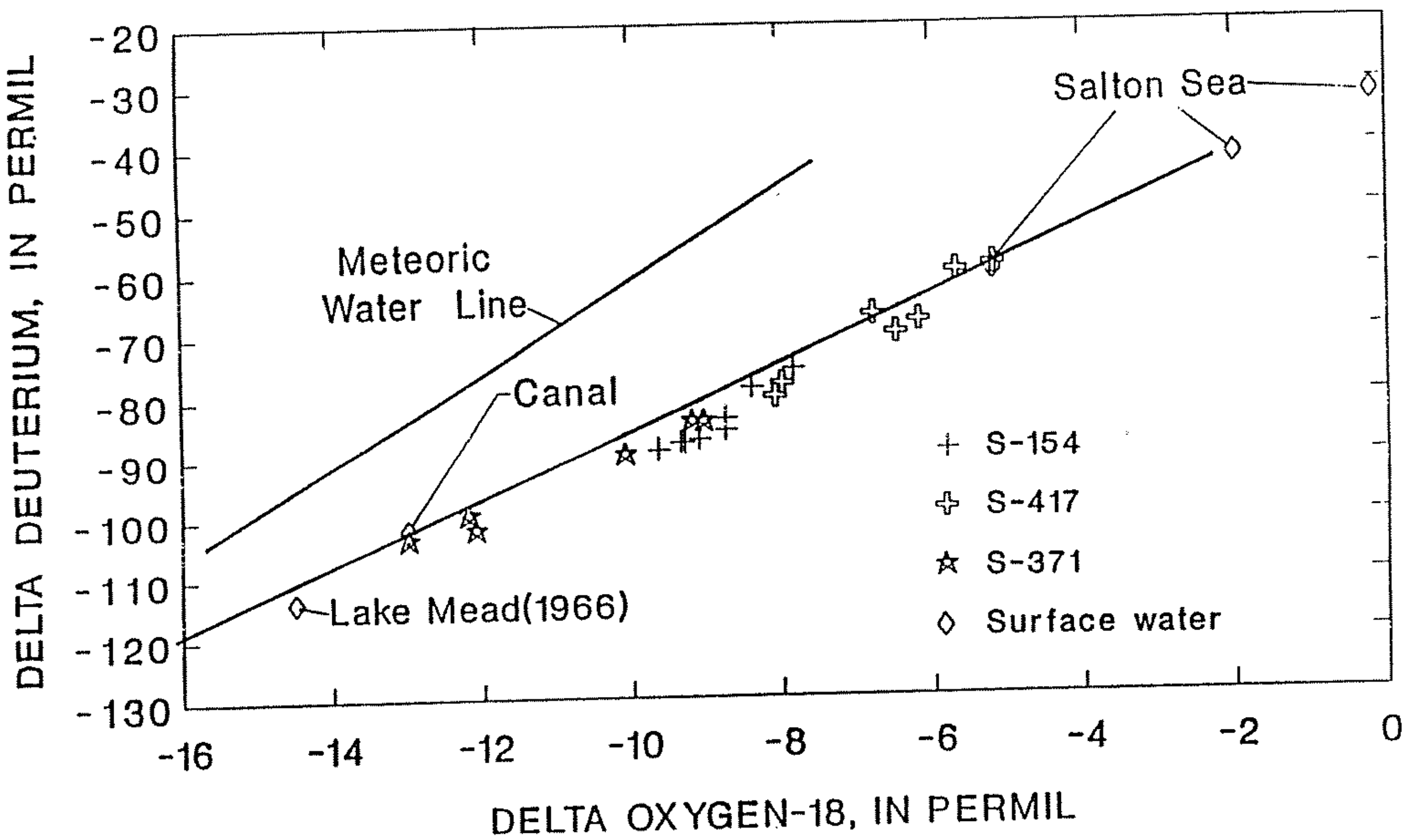


Figure 26. Regression plot of hydrogen and oxygen isotopes and the meteoric water line for water samples from wells and lysimeters at three sites in the Imperial Valley.

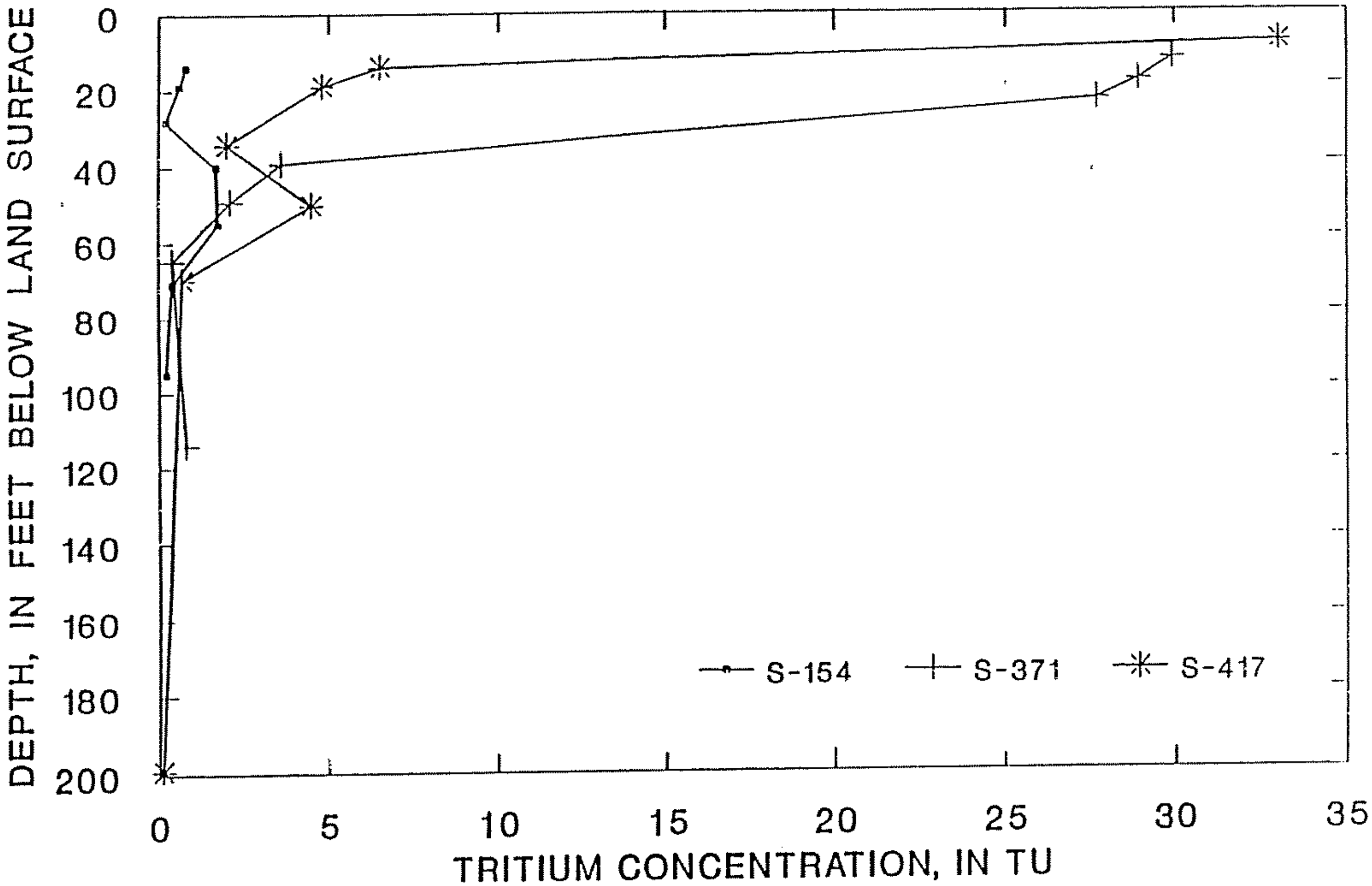


Figure 27. Tritium concentration in water samples from lysimeters and wells at selected fields in the Imperial Valley.

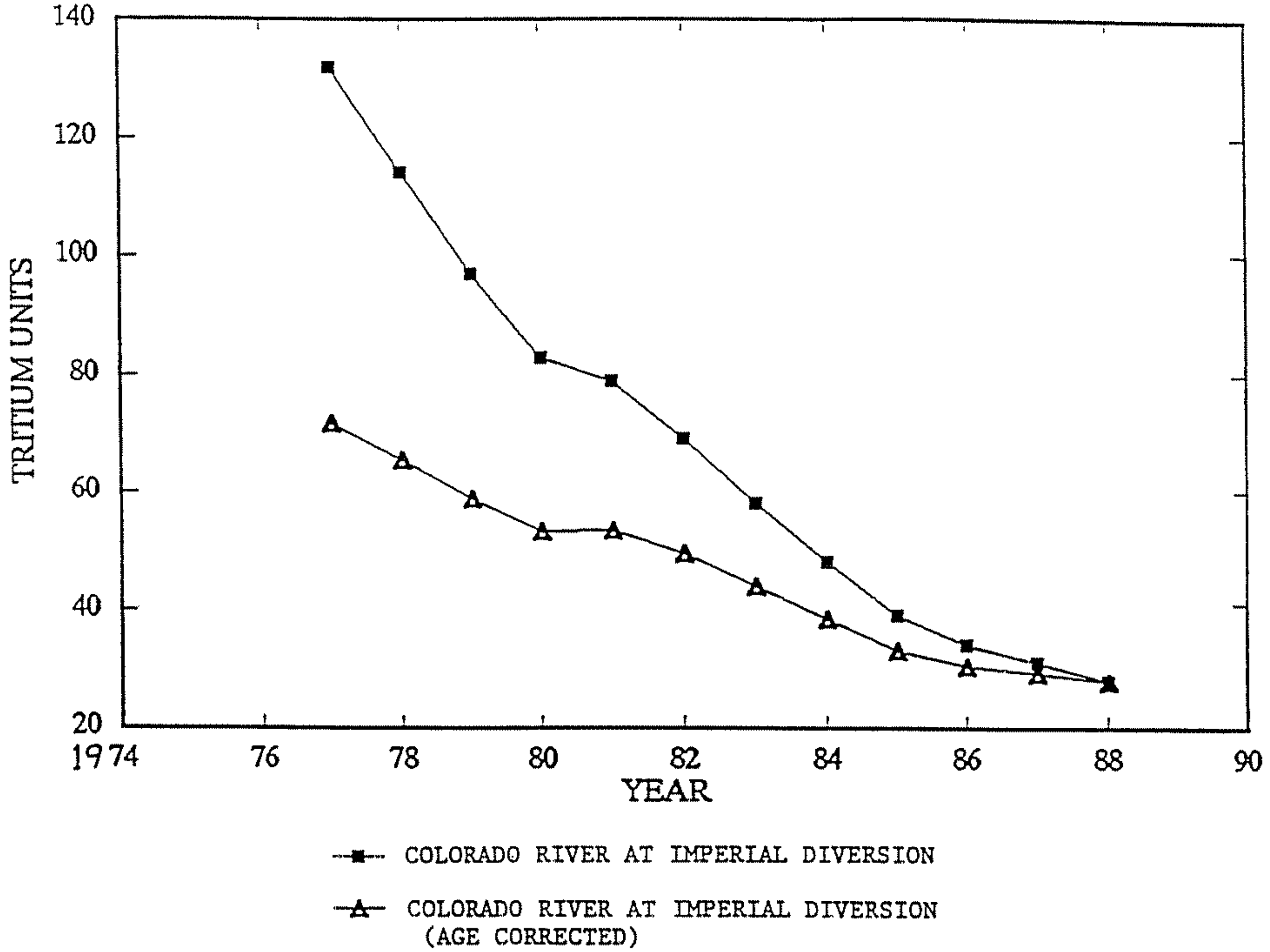


Figure 28. Tritium concentration in water samples from the Colorado River, 1974-88.

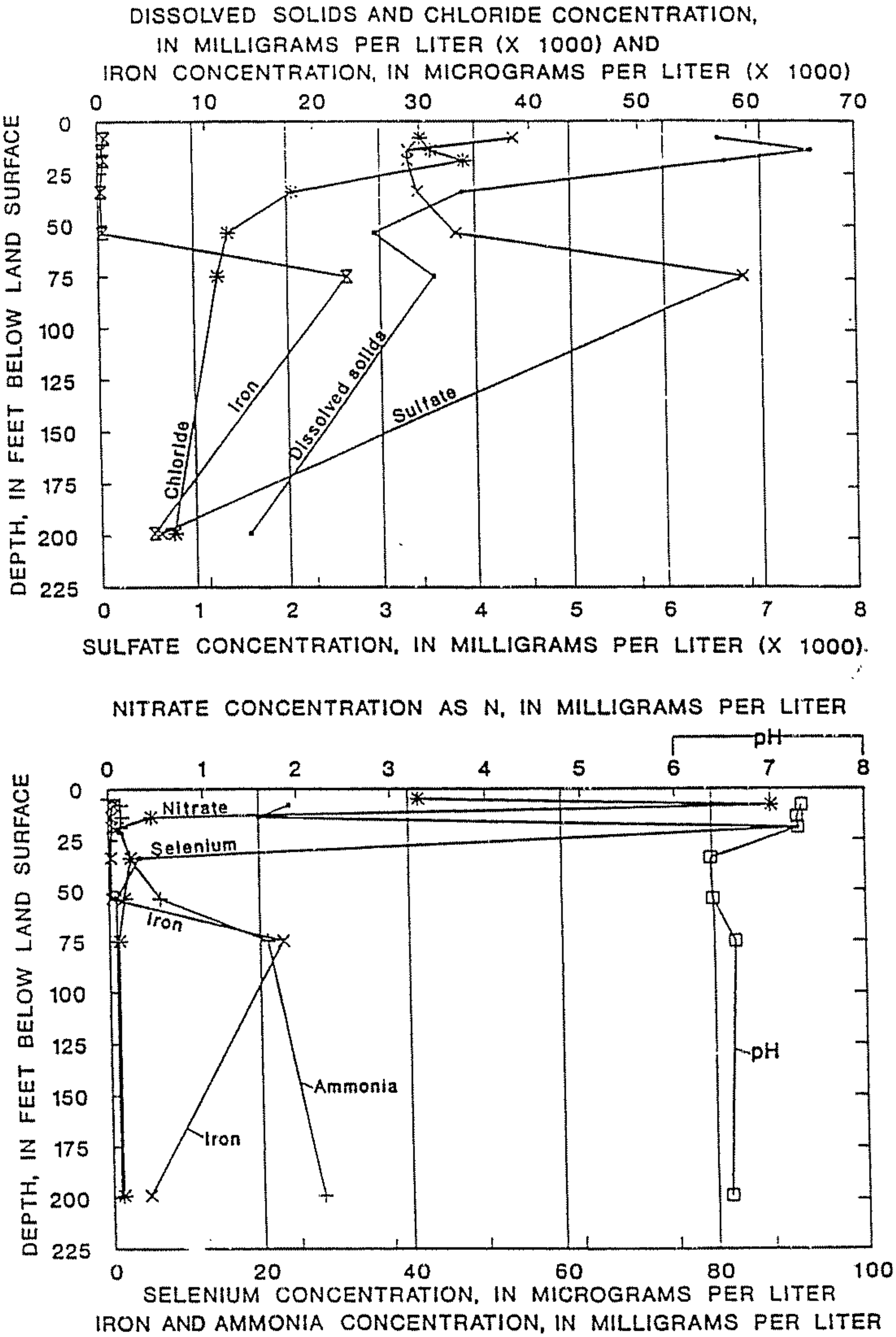
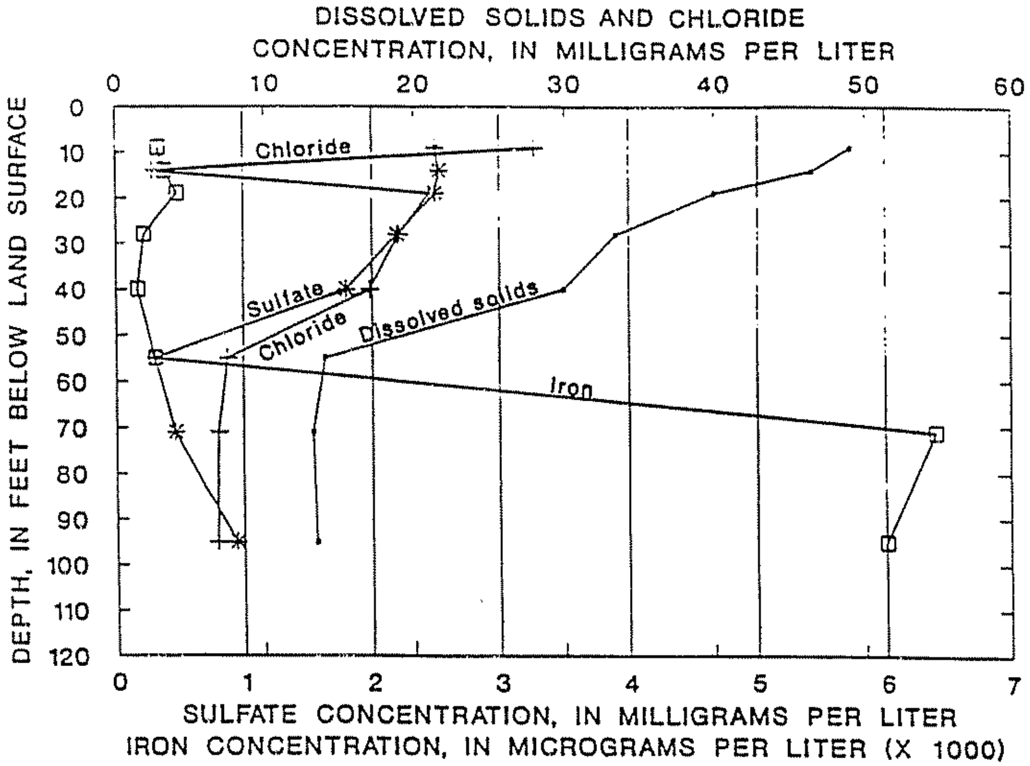


Figure 29. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the northern site (near S-417) in the Imperial Valley.



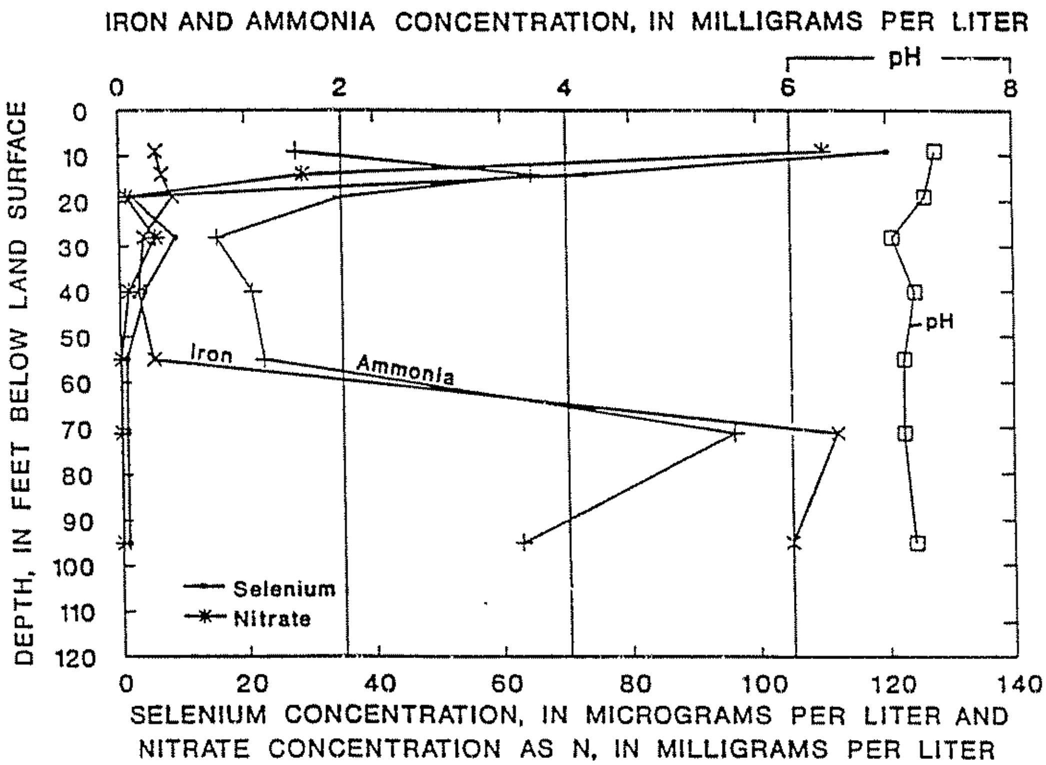


Figure 30. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the middle site (near S-154) in the Imperial Valley.

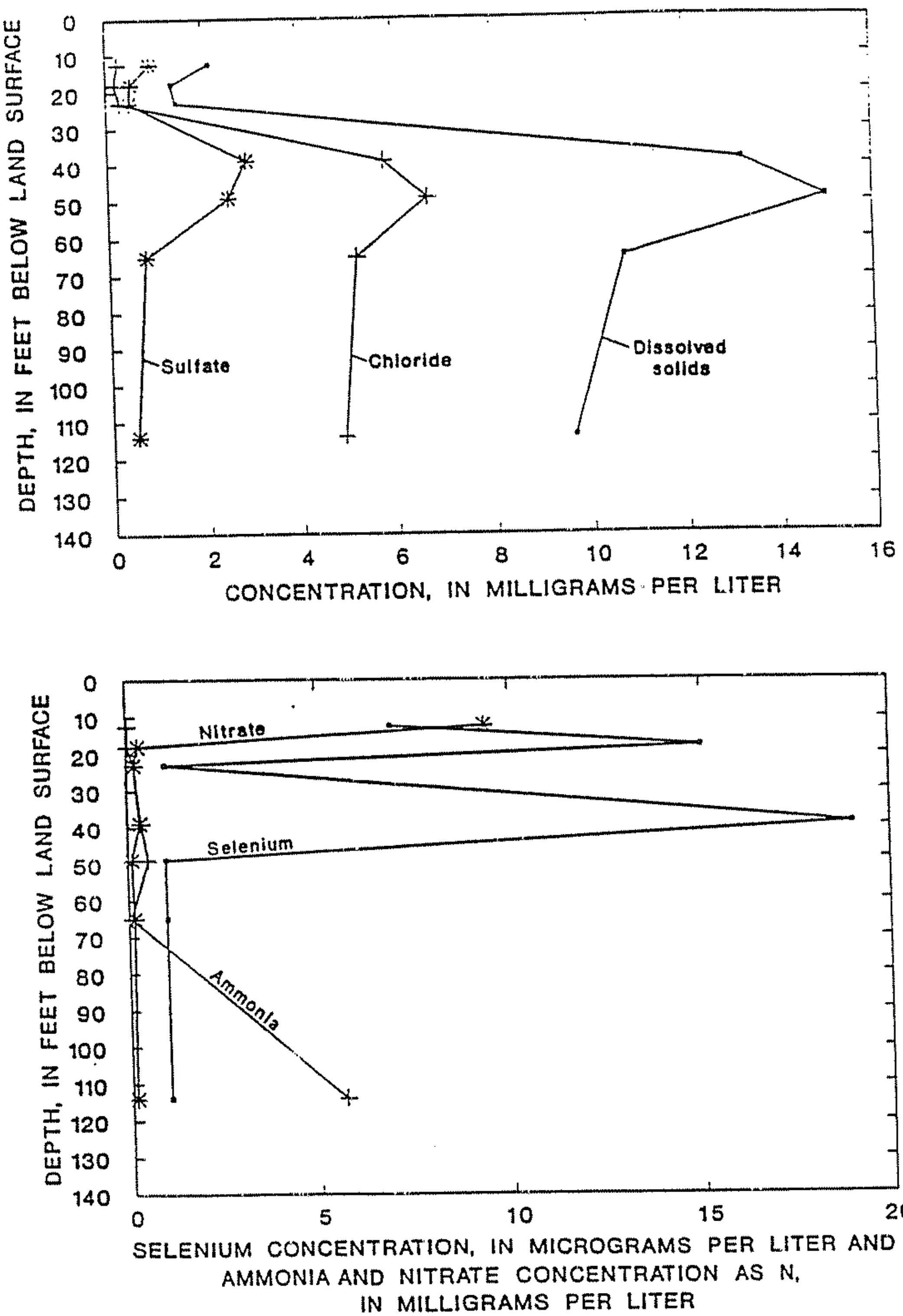
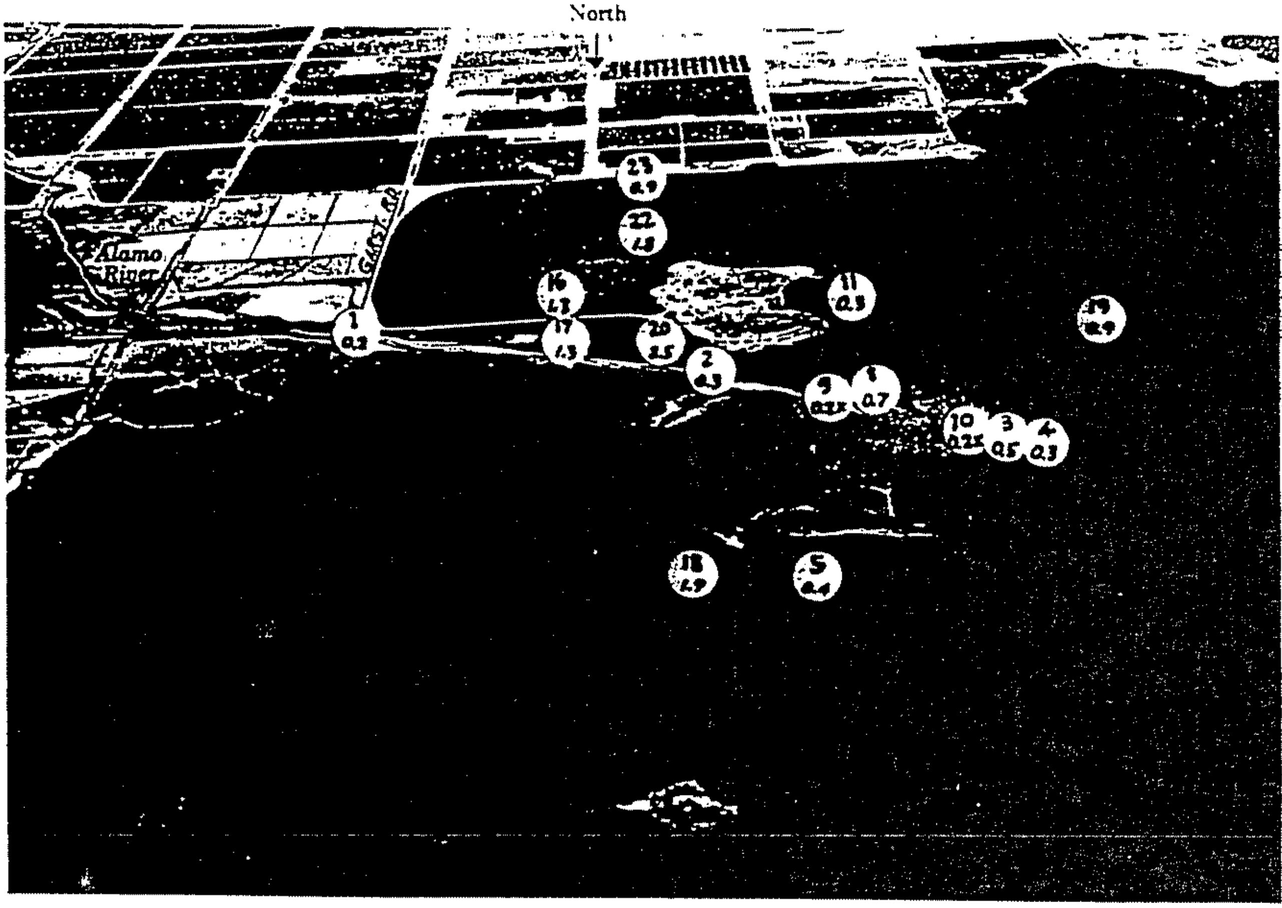


Figure 31. Concentrations of selected constituents, in relation to depth, for water samples collected from wells and lysimeters at the southern site (near S-371) in the Imperial Valley.



EXPLANATION

SITE NUMBER

SELENIUM CONCENTRATION - In micrograms per gram

Figure 32. Areal distribution of selenium in bottom sediments at the southern end of the Salton Sea.

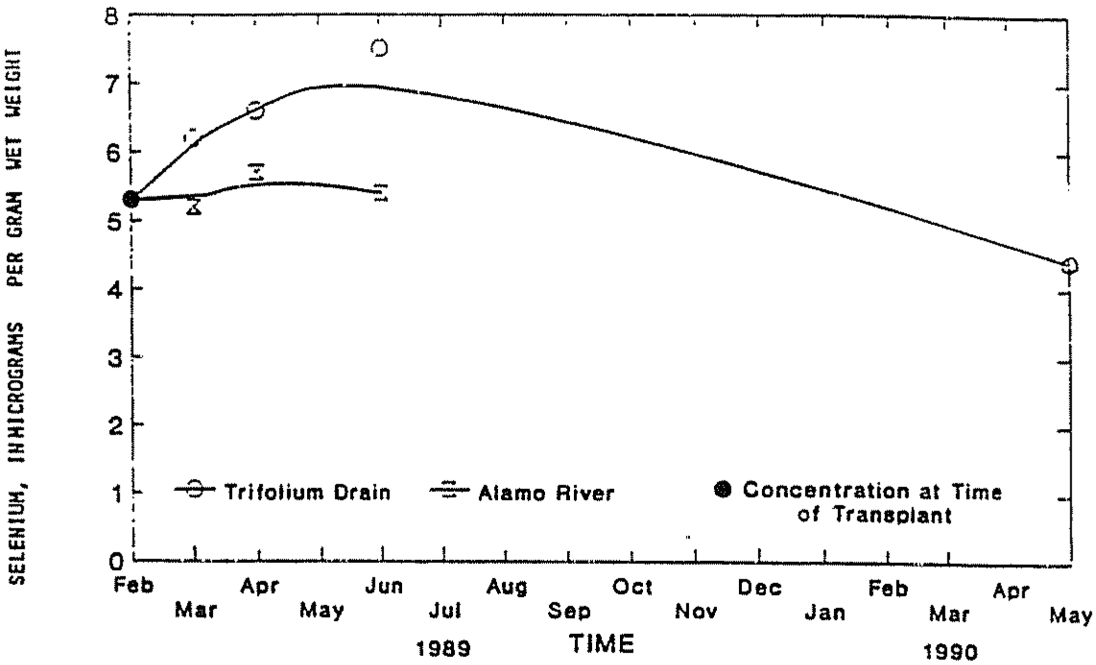


Figure 33. Selenium bioaccumulation in transplanted Asiatic river clams, 1989-90.

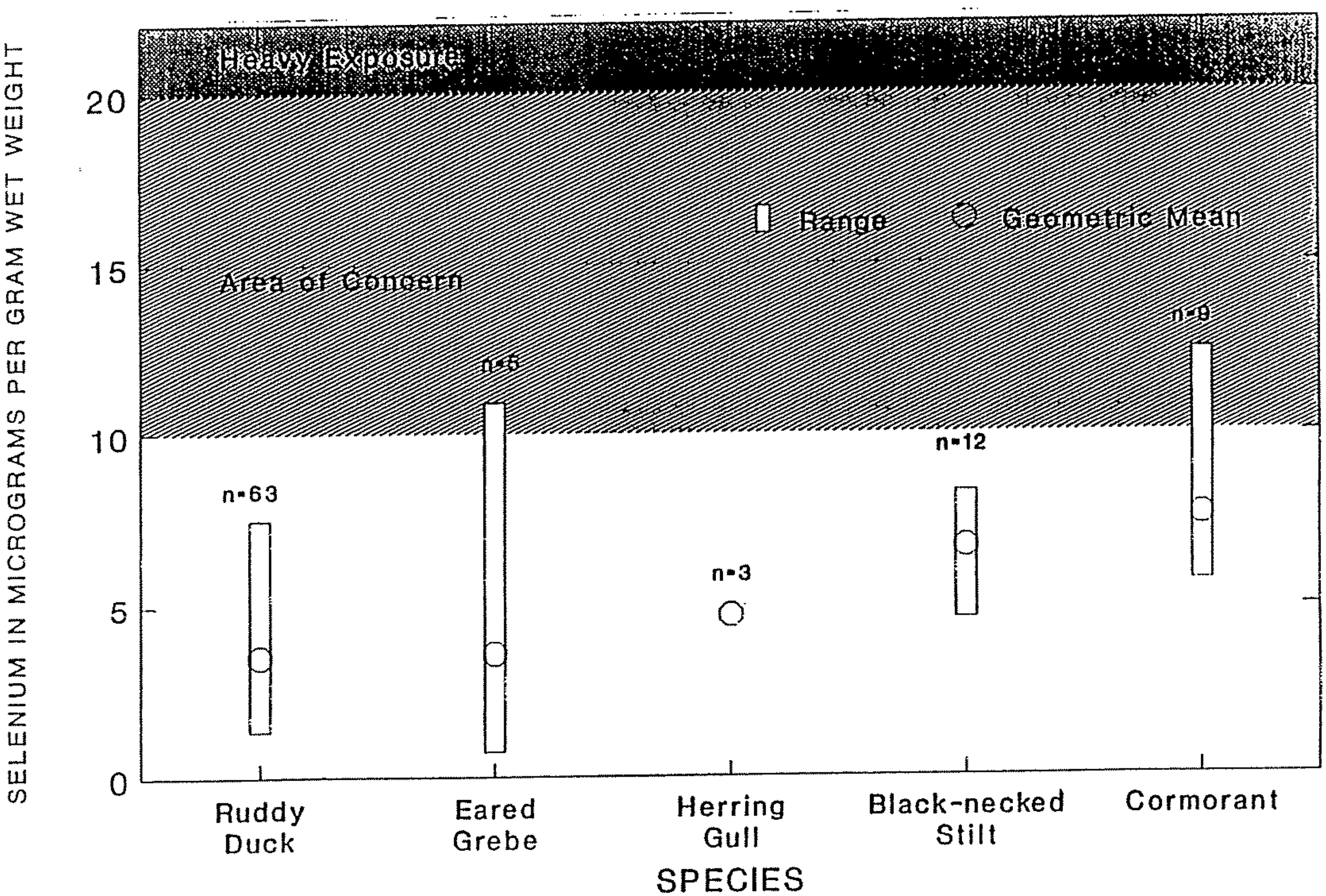


Figure 34. Selenium exposure levels in livers of water birds and shorebirds utilizing the Salton Sea.

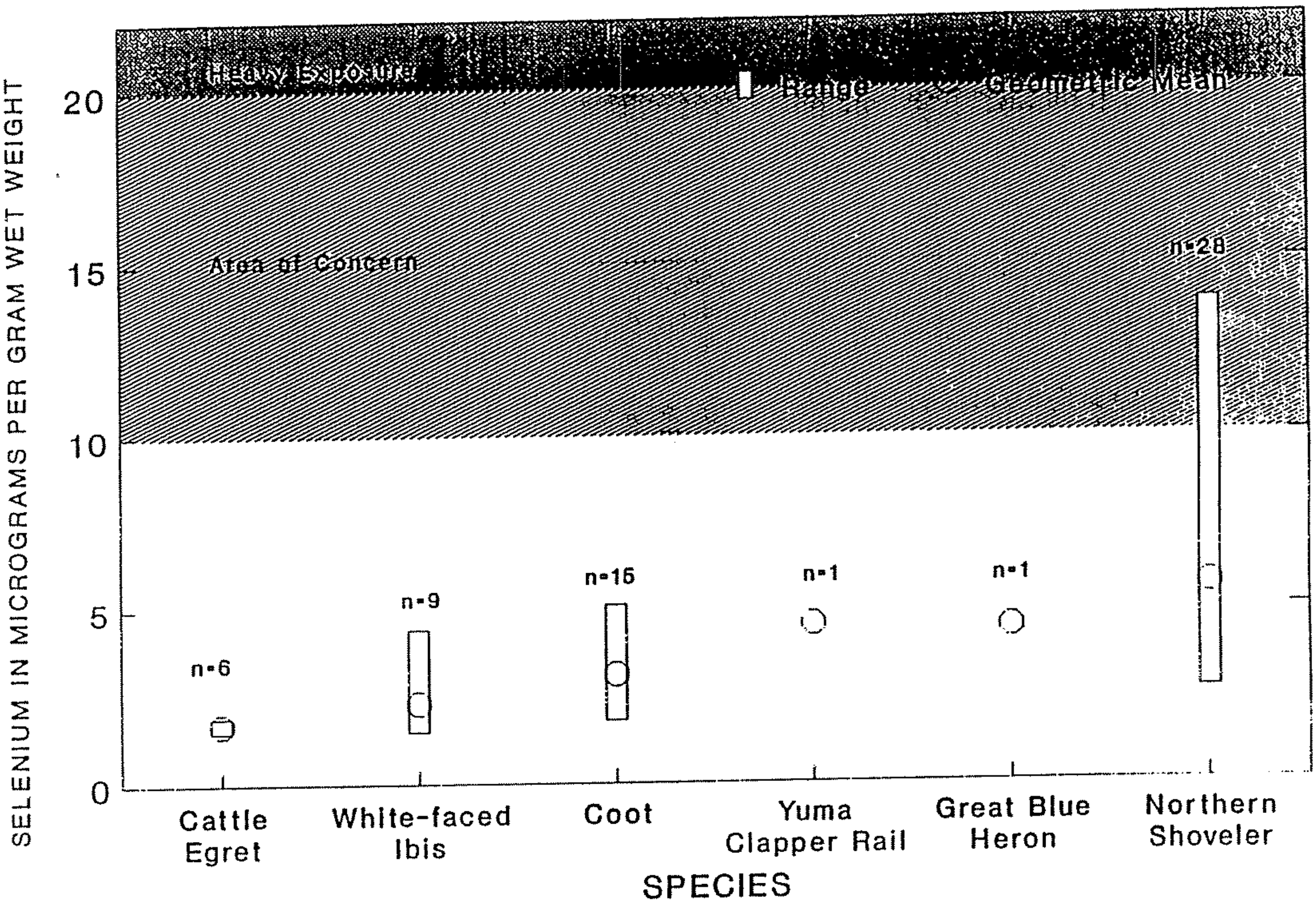


Figure 35. Selenium exposure levels in livers of water birds and shorebirds utilizing rivers and drains.

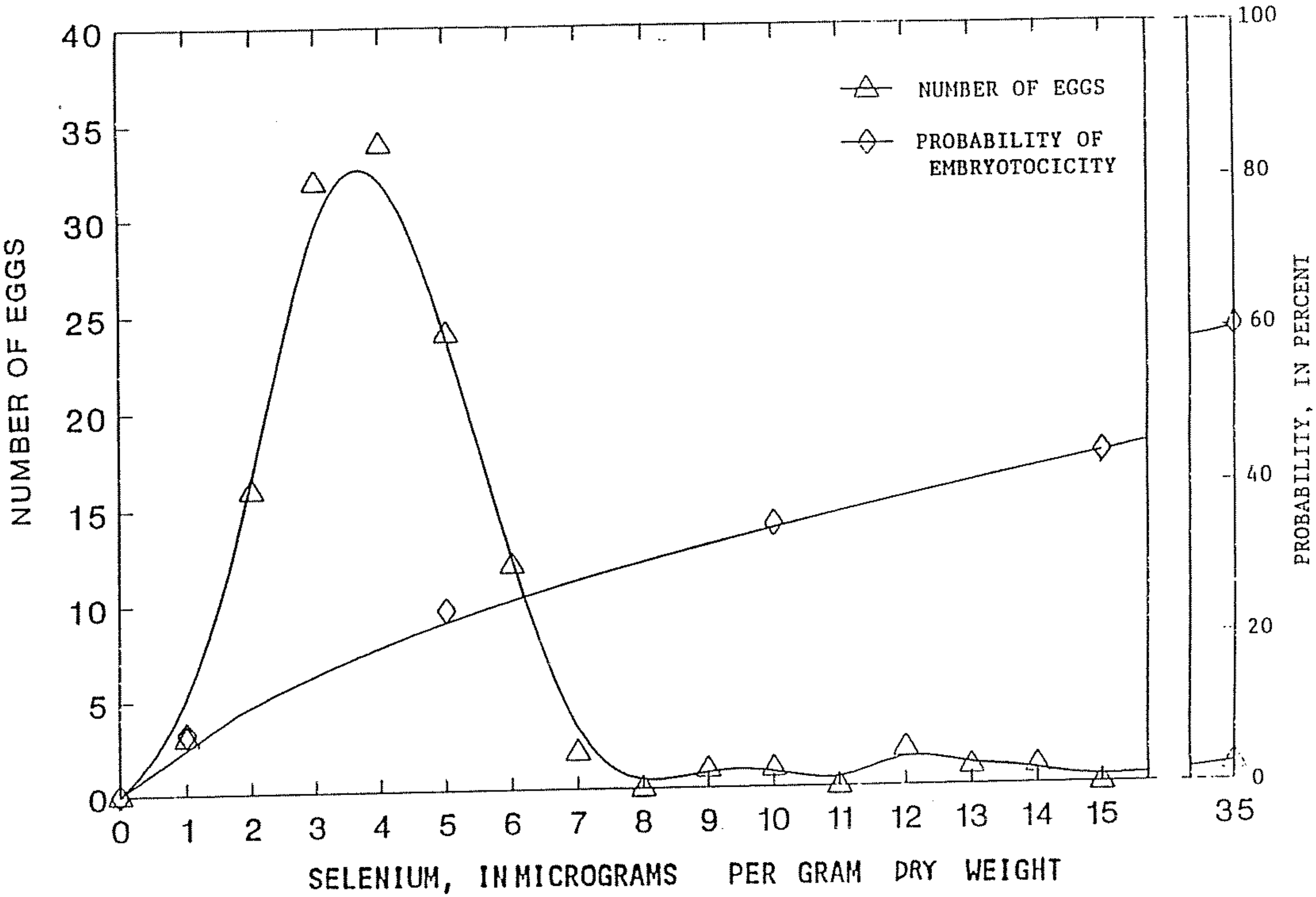


Figure 36. Cumulative distribution of selenium in black-necked stilt eggs from the Salton Sea 1988-89.

Figure 37

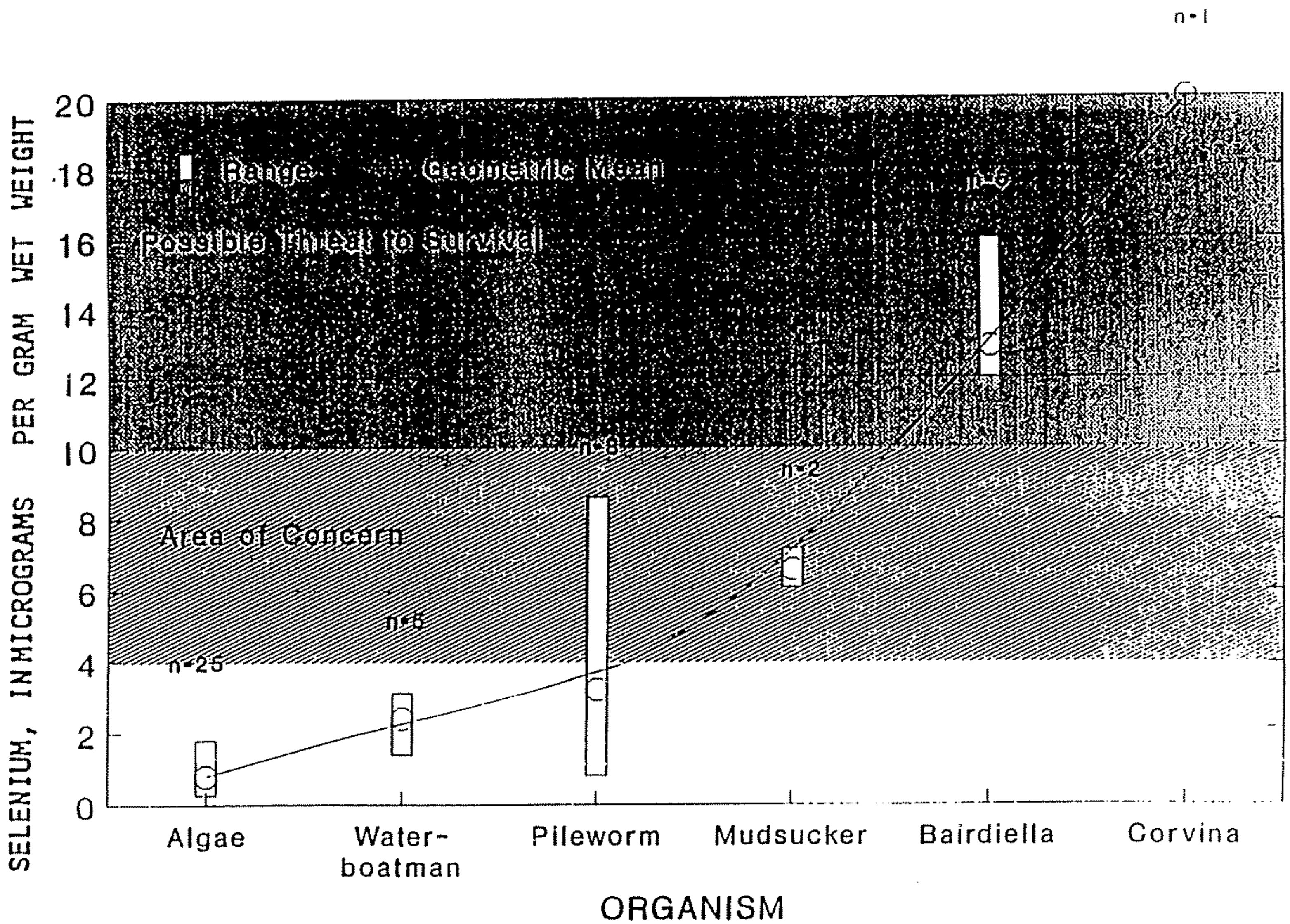


Figure 38. Selenium concentration in food-chain organisms of the Salton Sea.

Figure 39

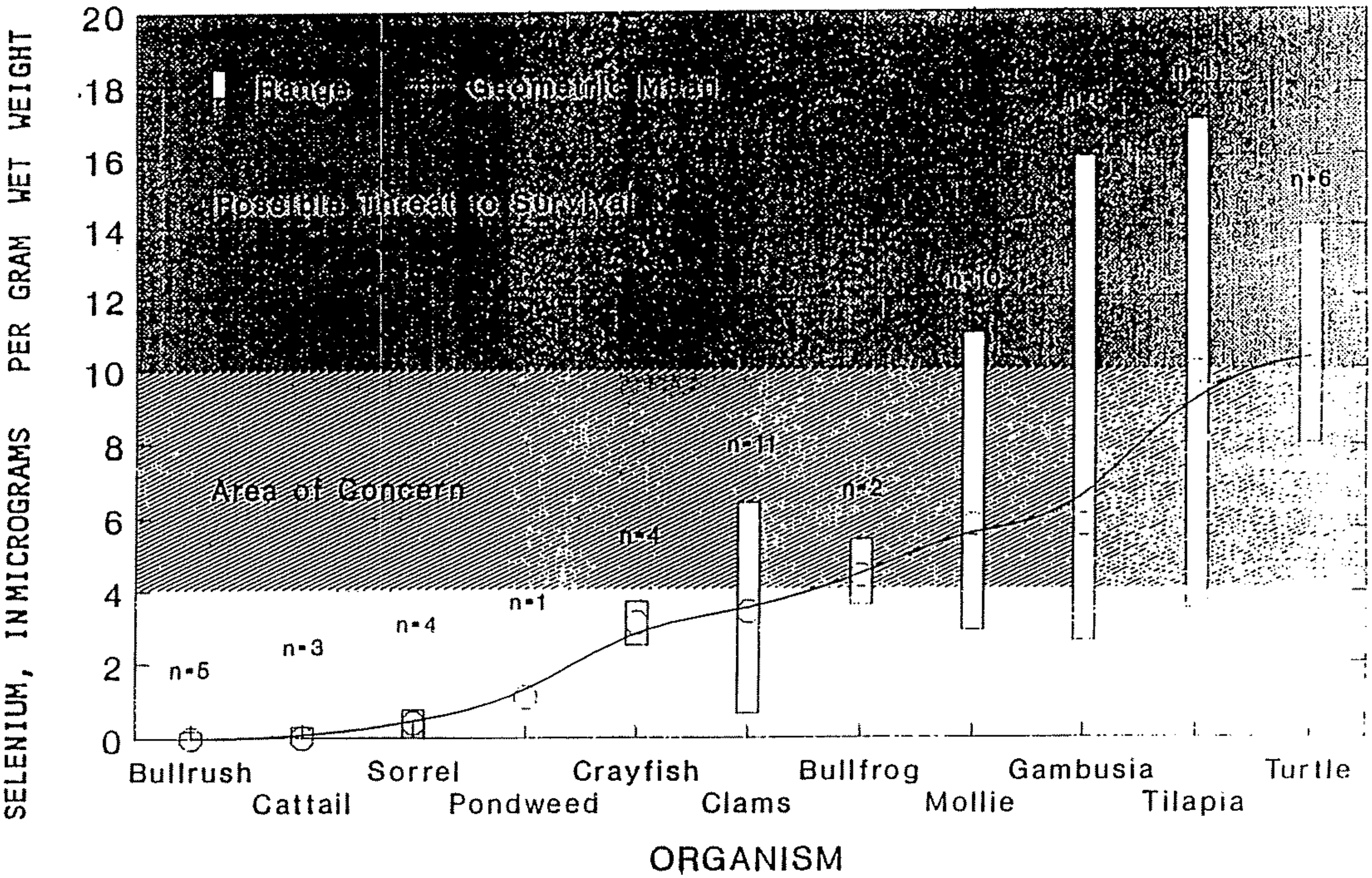


Figure 40. Selenium concentration in food-chain organisms of river and drains.

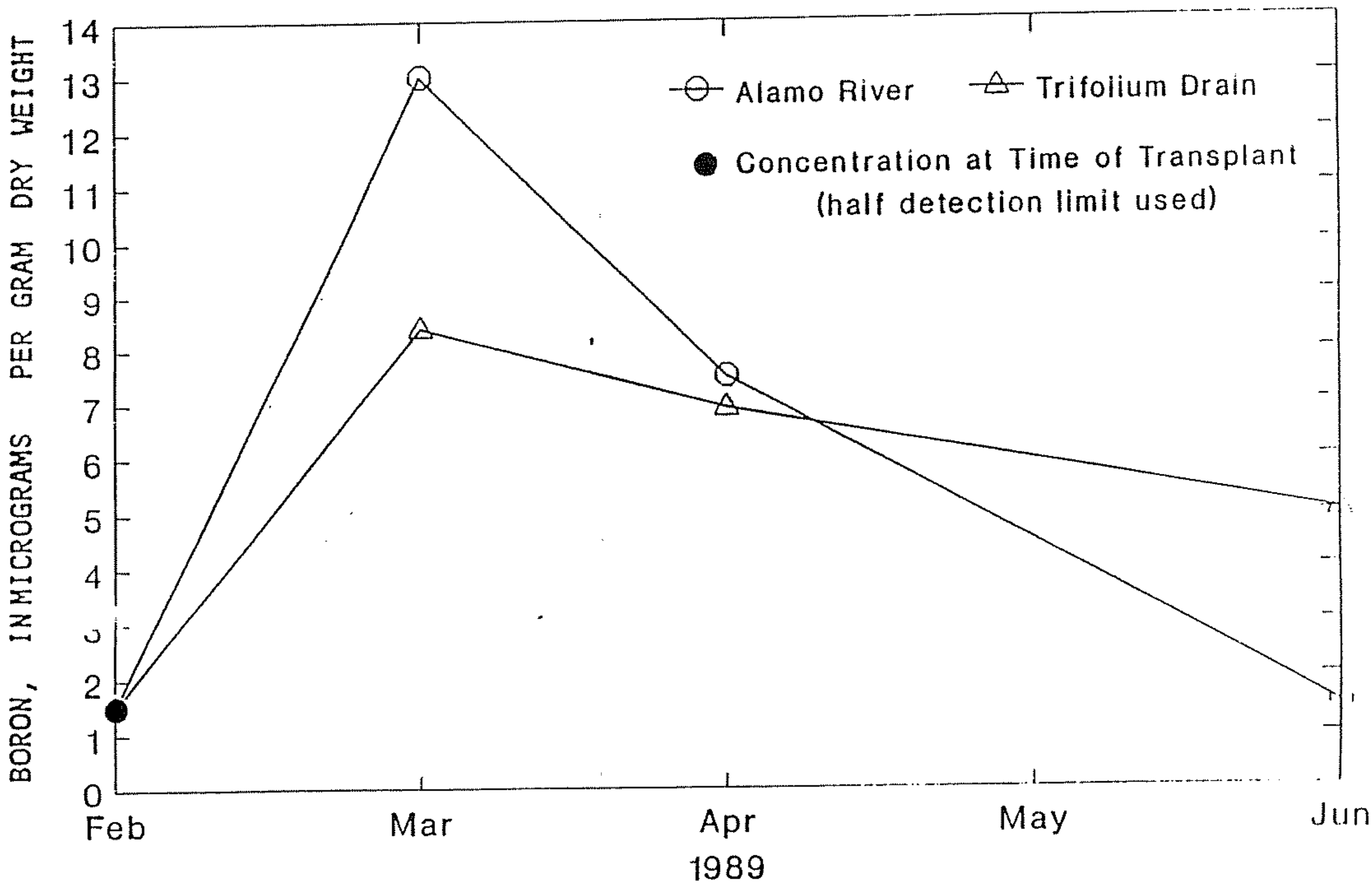


Figure 41. Boron bioaccumulation in transplanted Asiatic river clams.

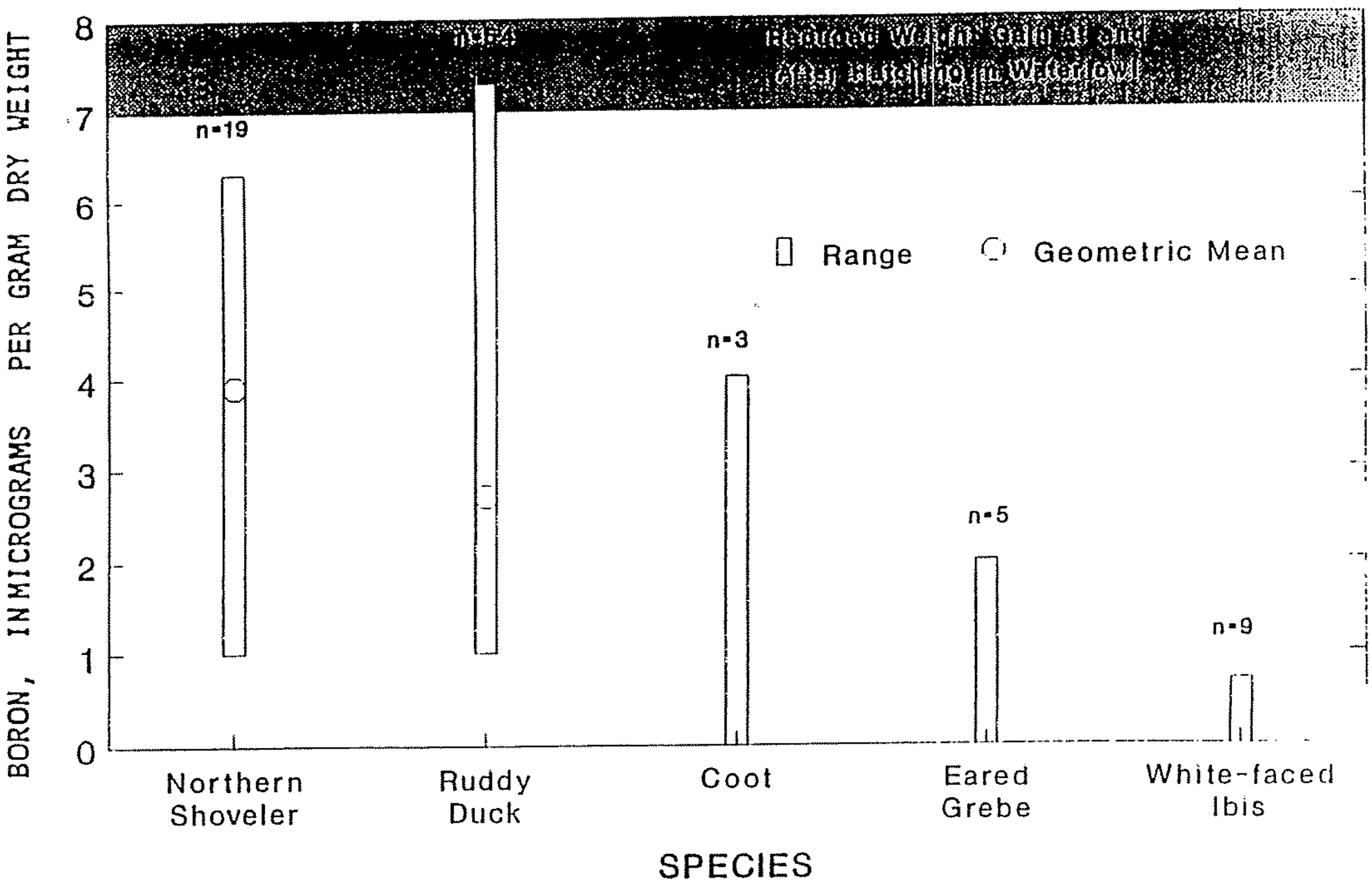


Figure 42. Boron concentration in livers of water birds and shorebirds from the Salton Sea area.

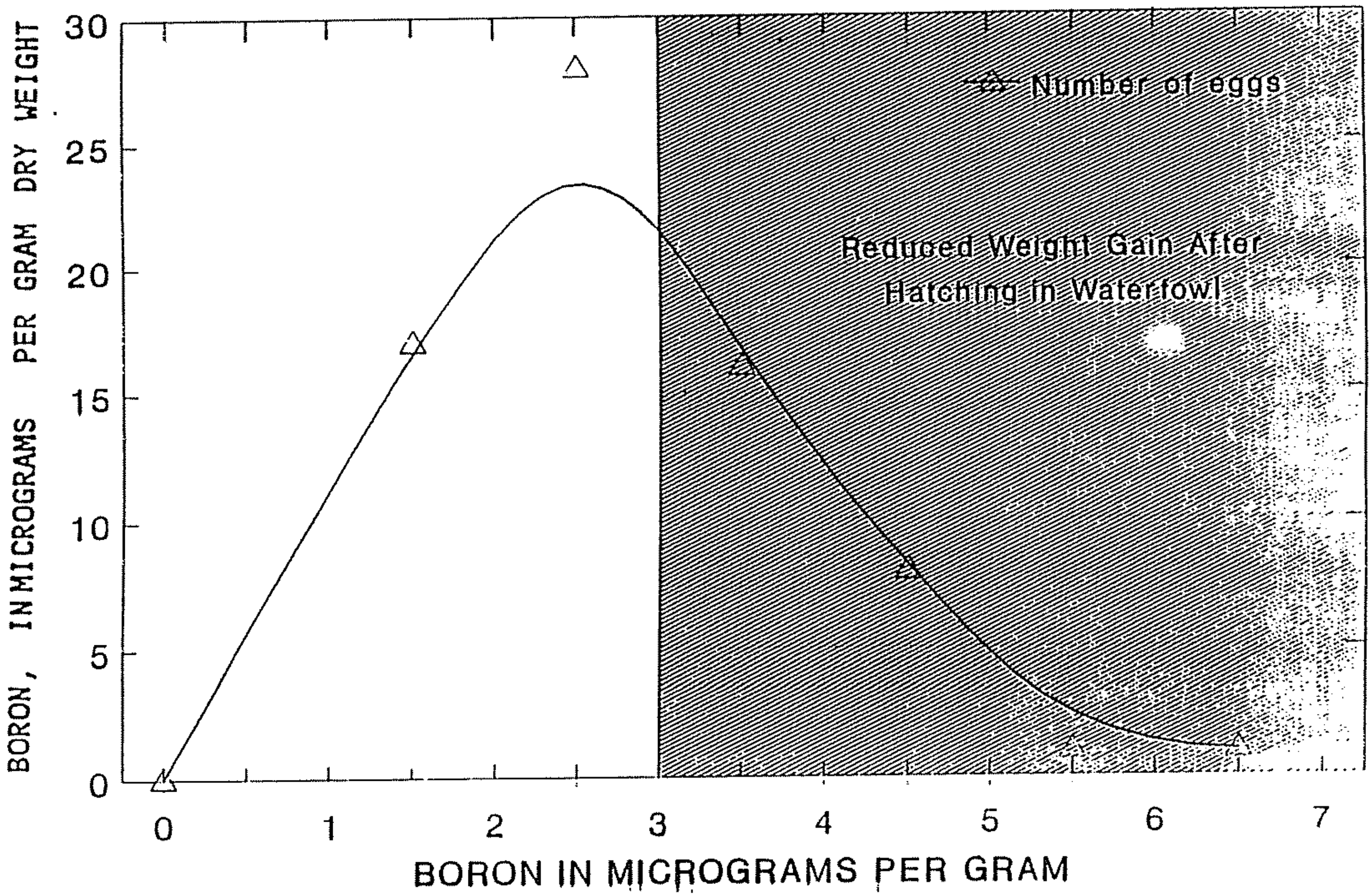


Figure 43. Cumulative distribution of boron in black-necked stilt eggs from the Salton Sea.

Figure 44

Figure 45

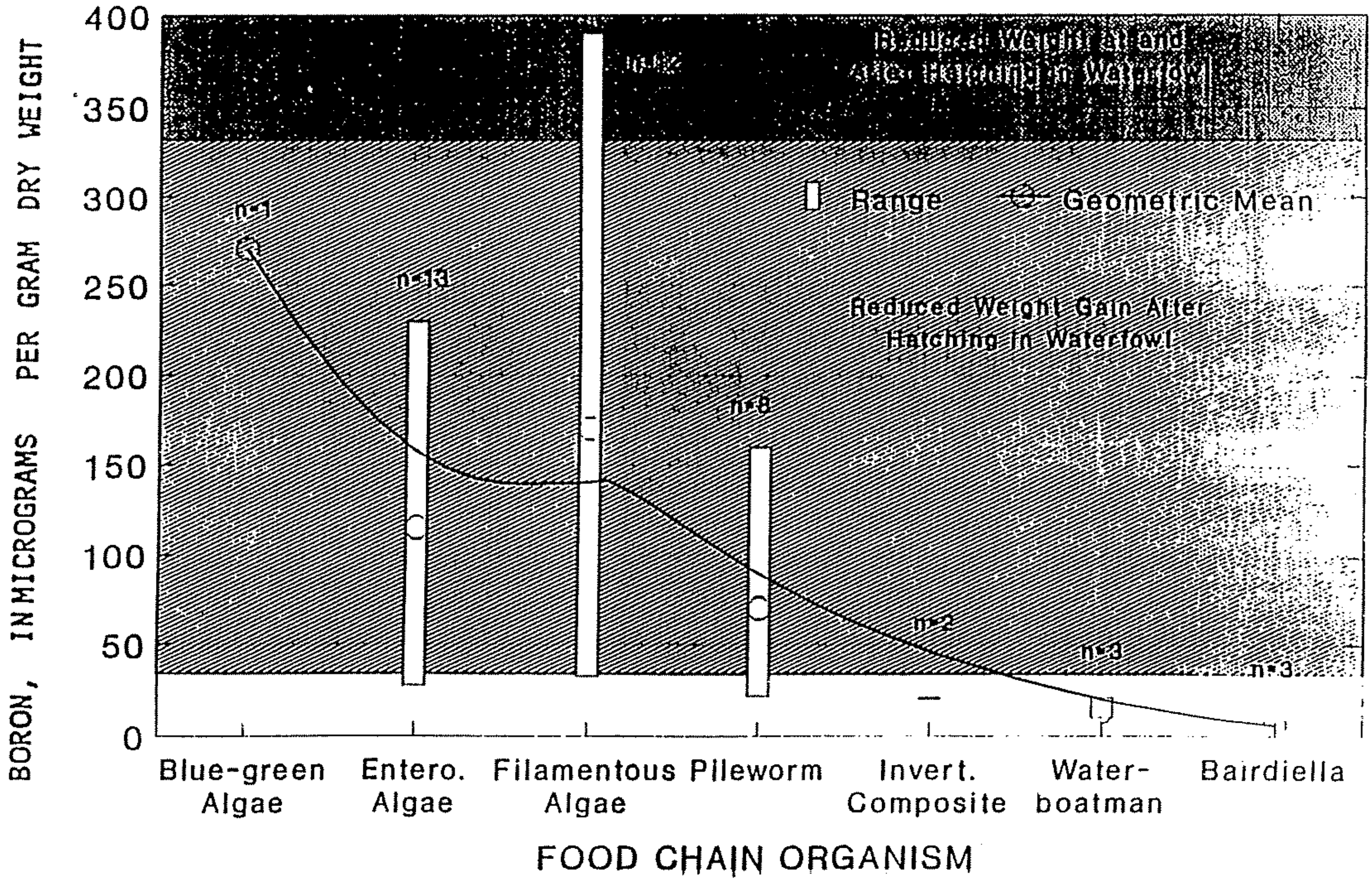


Figure 46. Boron concentration in food-chain organisms of the Salton Sea, 1986-

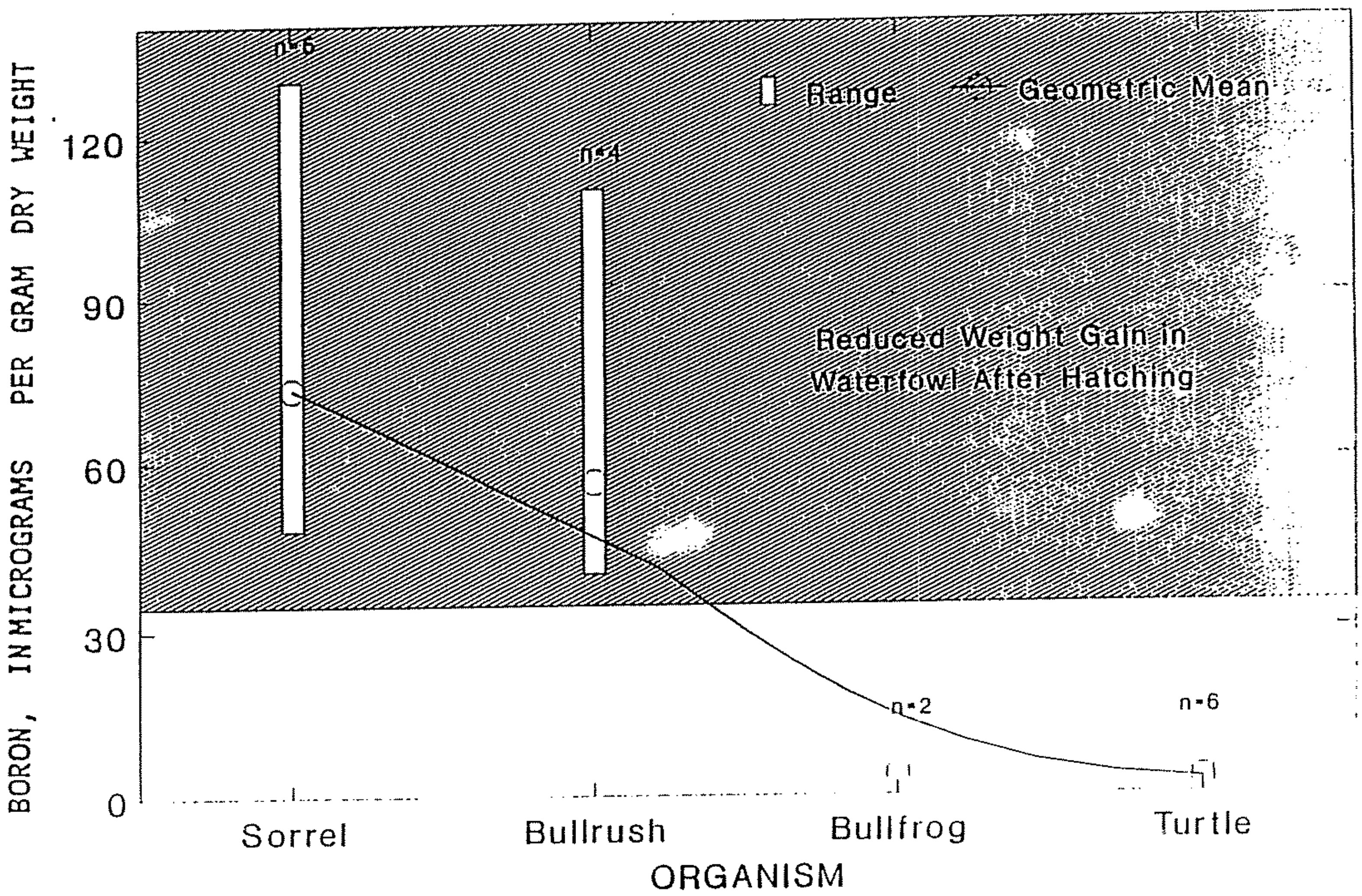


Figure 47. Boron concentration in food-chain organisms of rivers and drains.

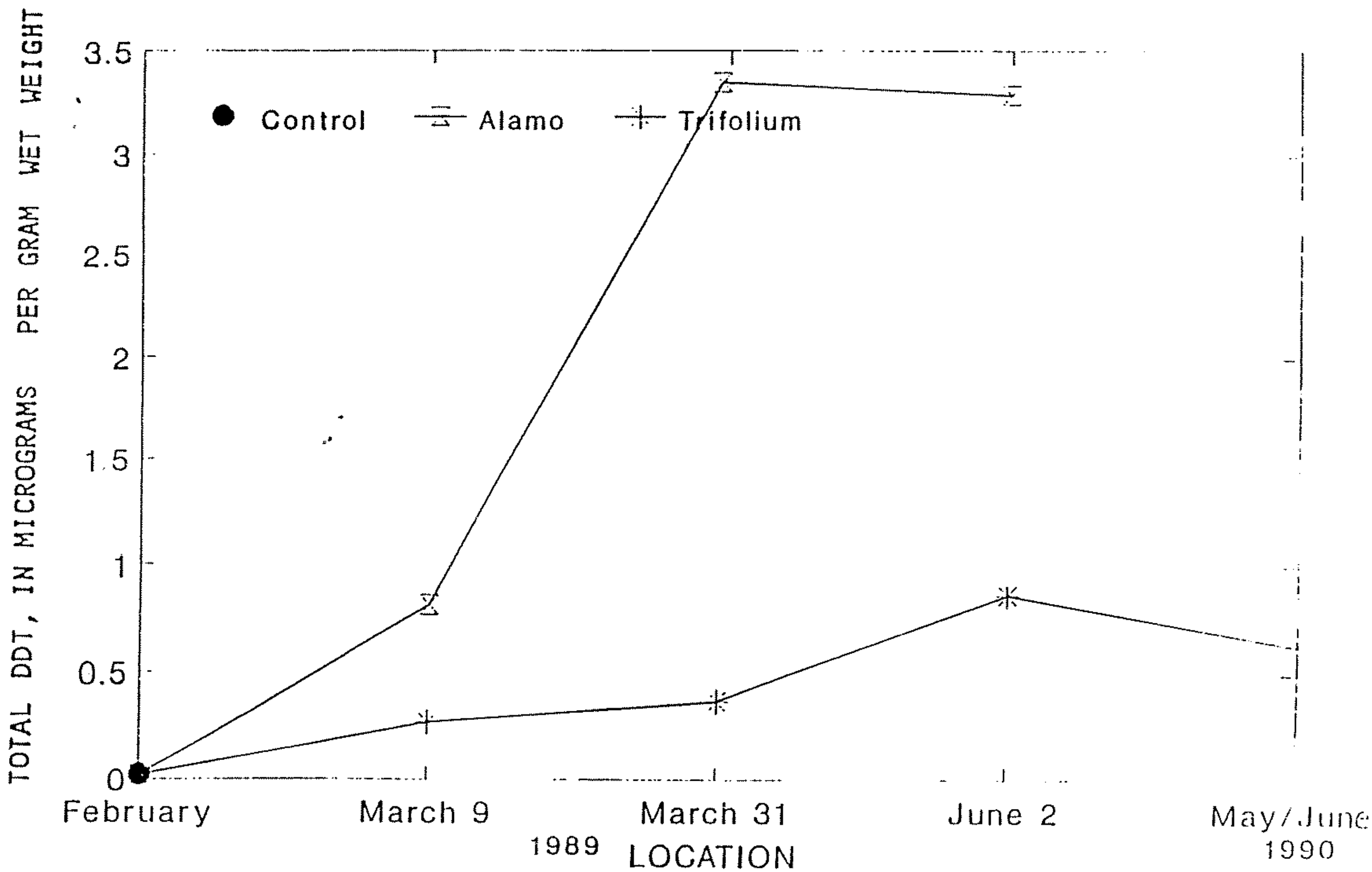


Figure 48. DDT concentration in transplanted Asiatic river clams.

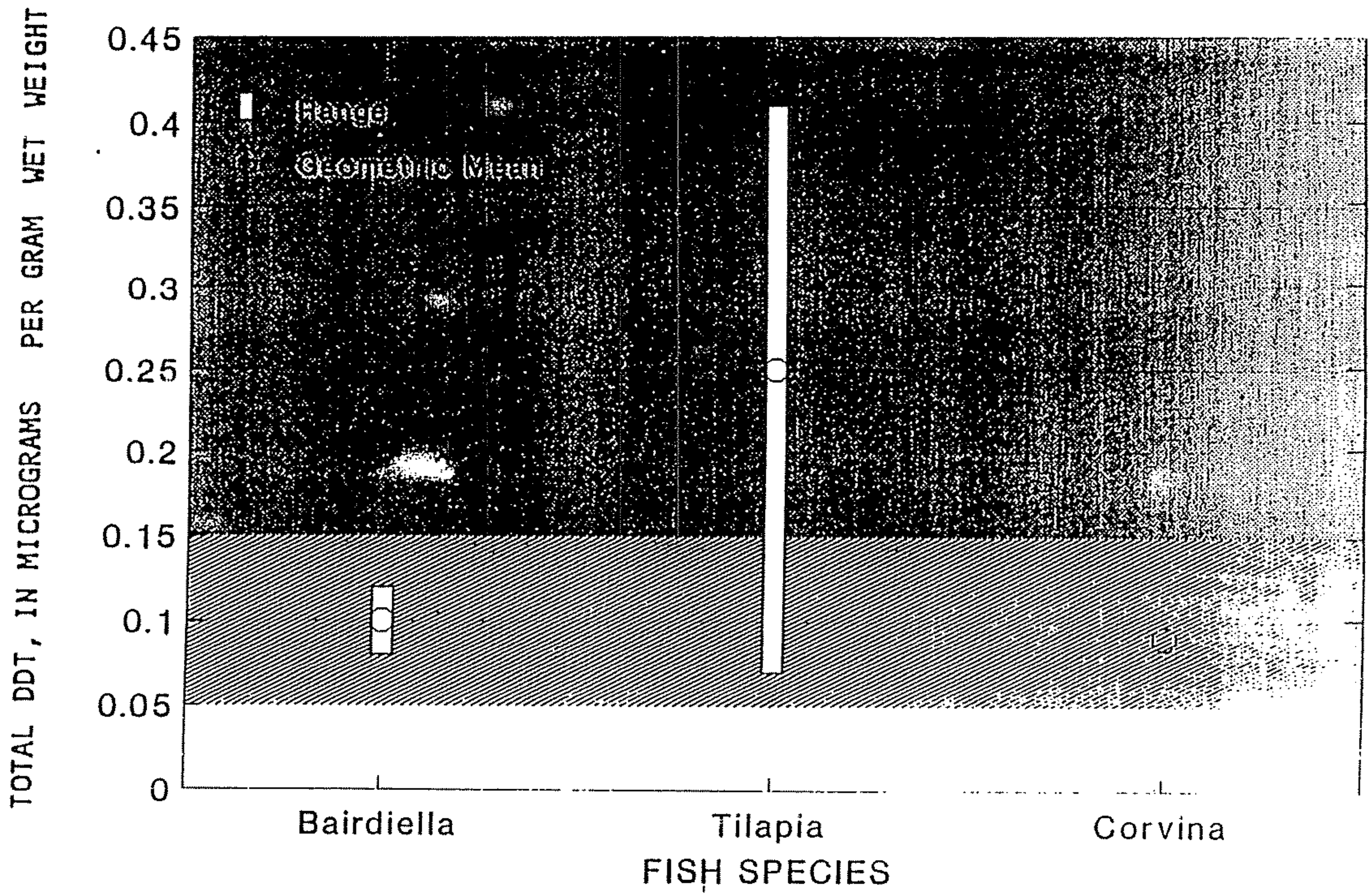


Figure 49. Total DDT concentration for three species of fish from the Salton Sea.

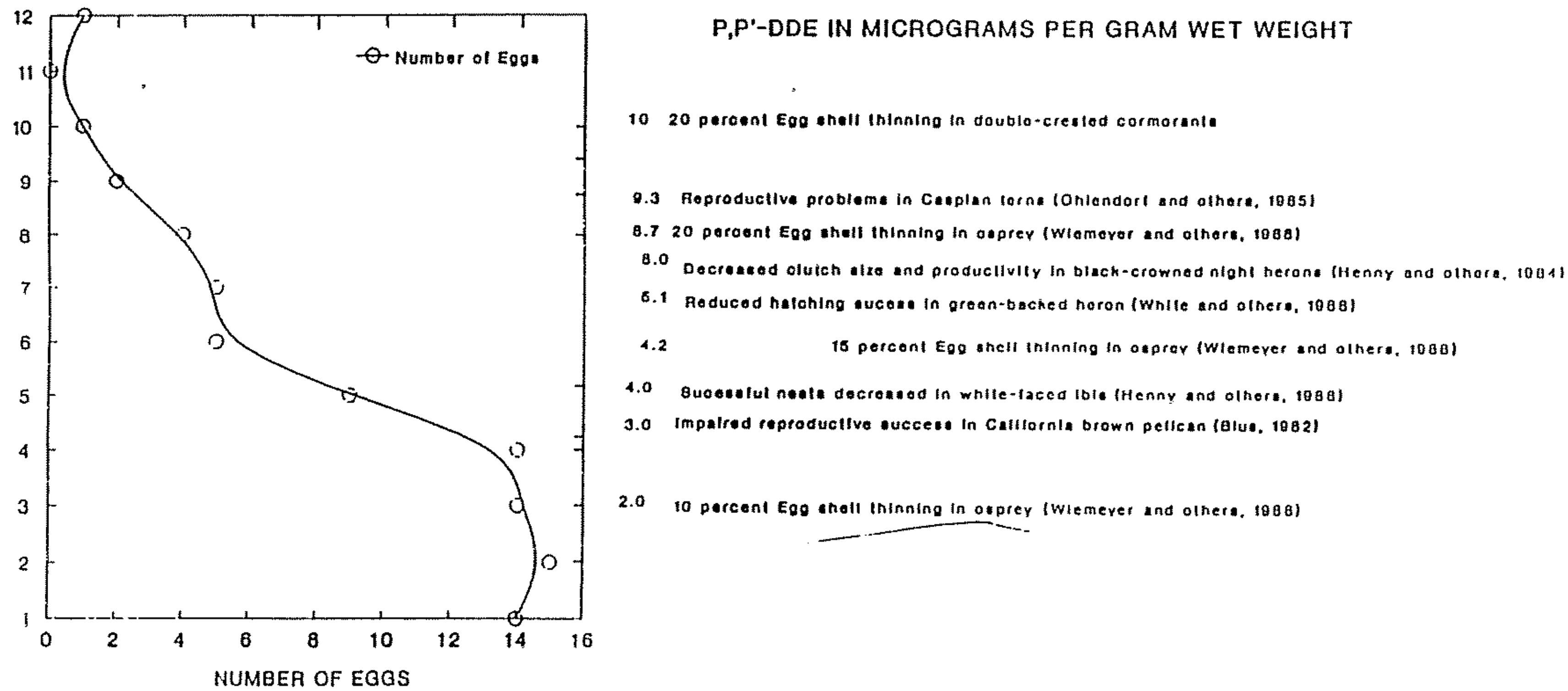


Figure 50. DDT concentrations in black-necked stilt eggs and reproductive-impairment thresholds for various bird species.

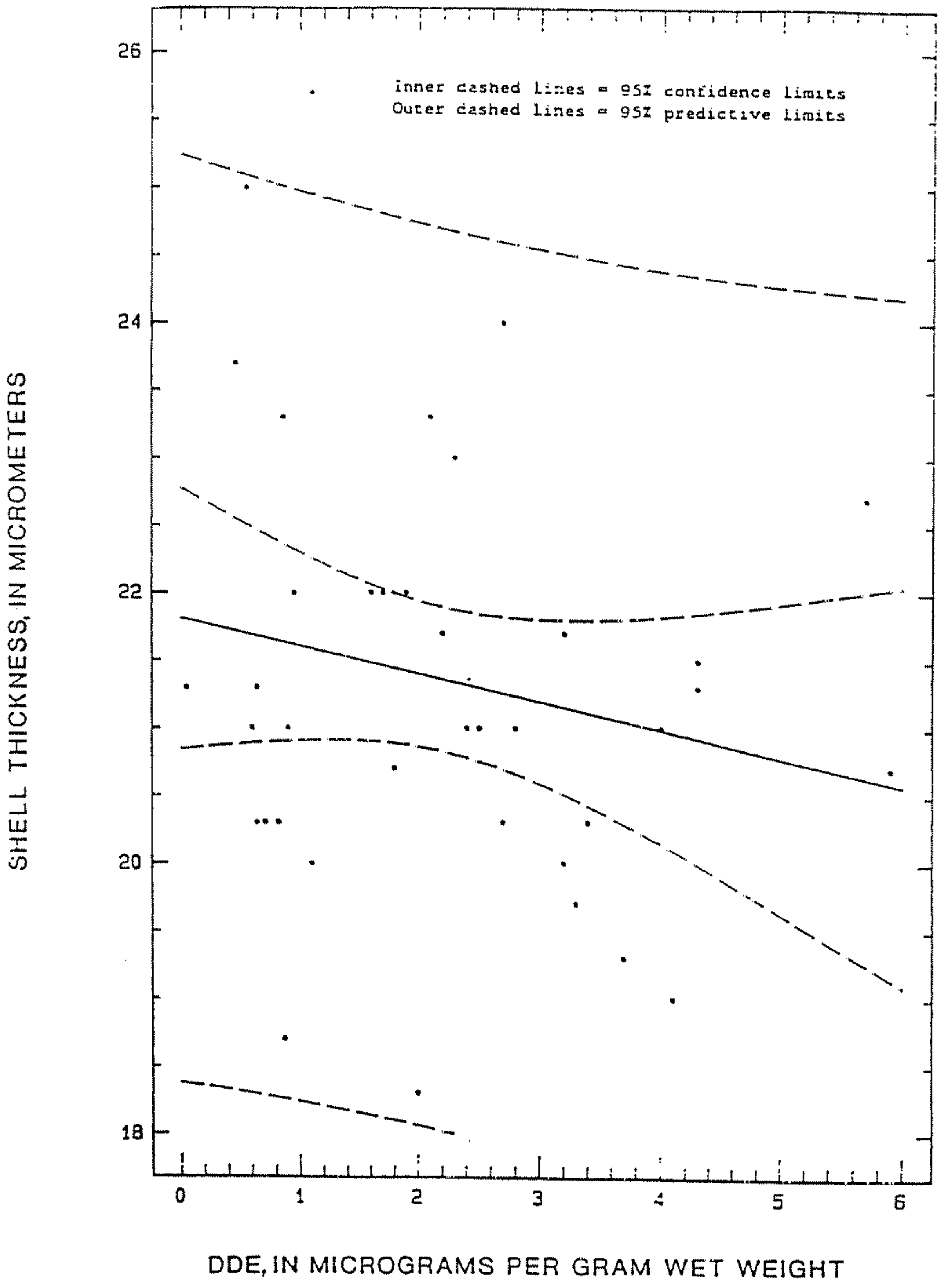


Figure 51. Correlation between DDE concentration and eggshell thickness for black-necked stilts from the Salton Sea, 1988-89.

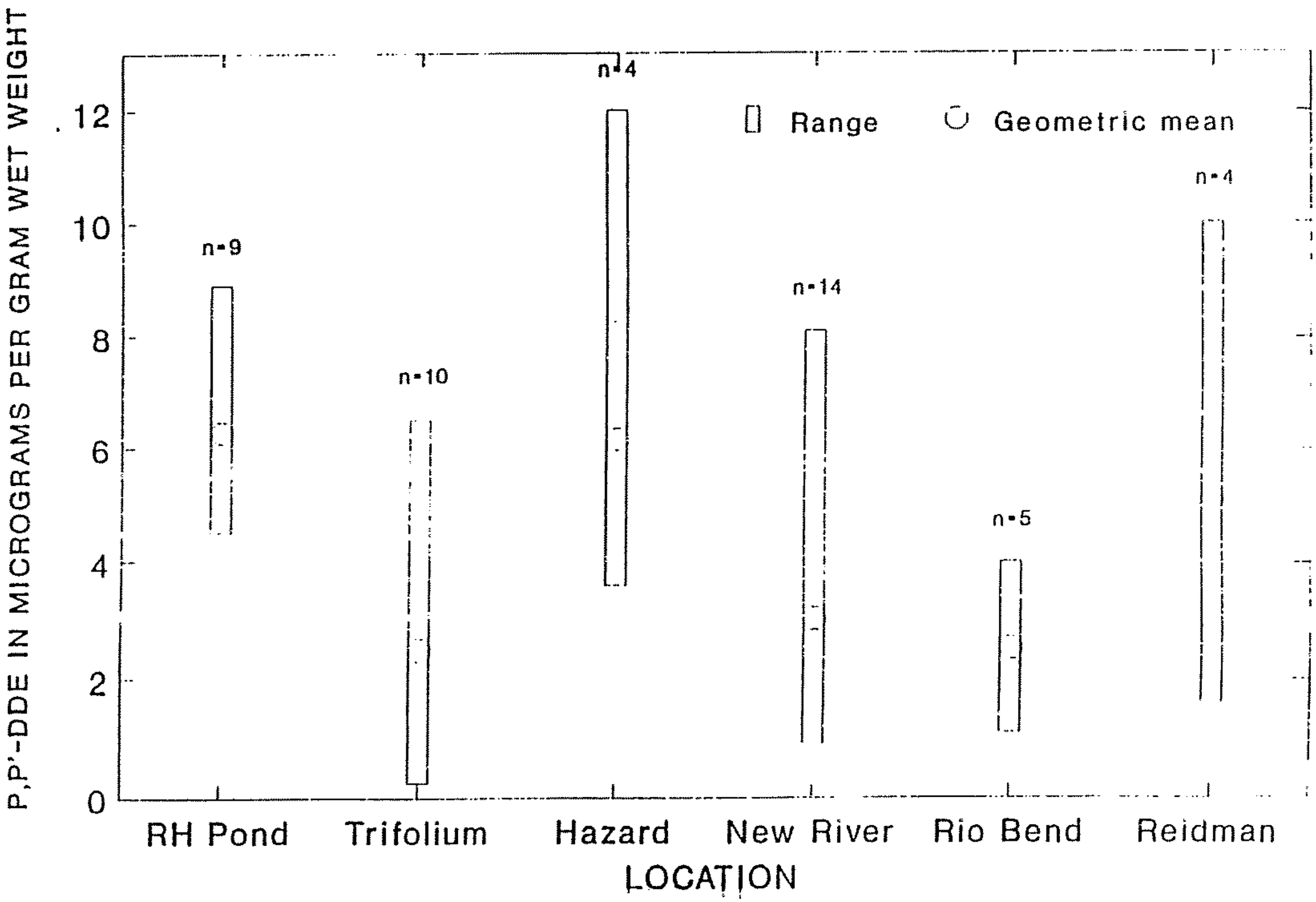


Figure 52. p,p'-DDE concentration in black-necked stilt eggs from selected nesting populations in the Salton Sea area, 1988-1989.

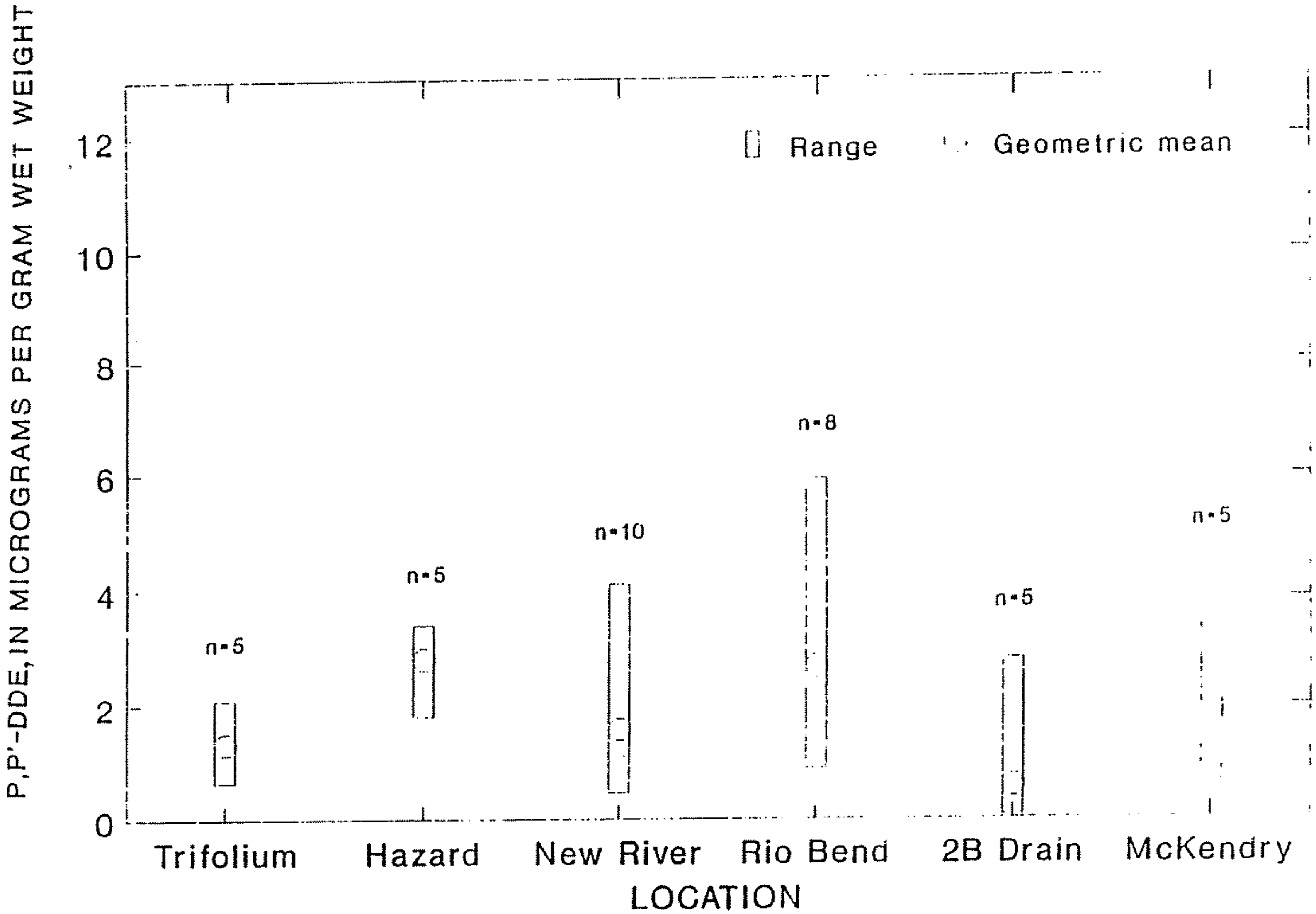


Figure 53. DDE concentration in black-necked stilt eggs from selected nesting populations in the Salton Sea area, 1989.

Figure 54

Figure 55

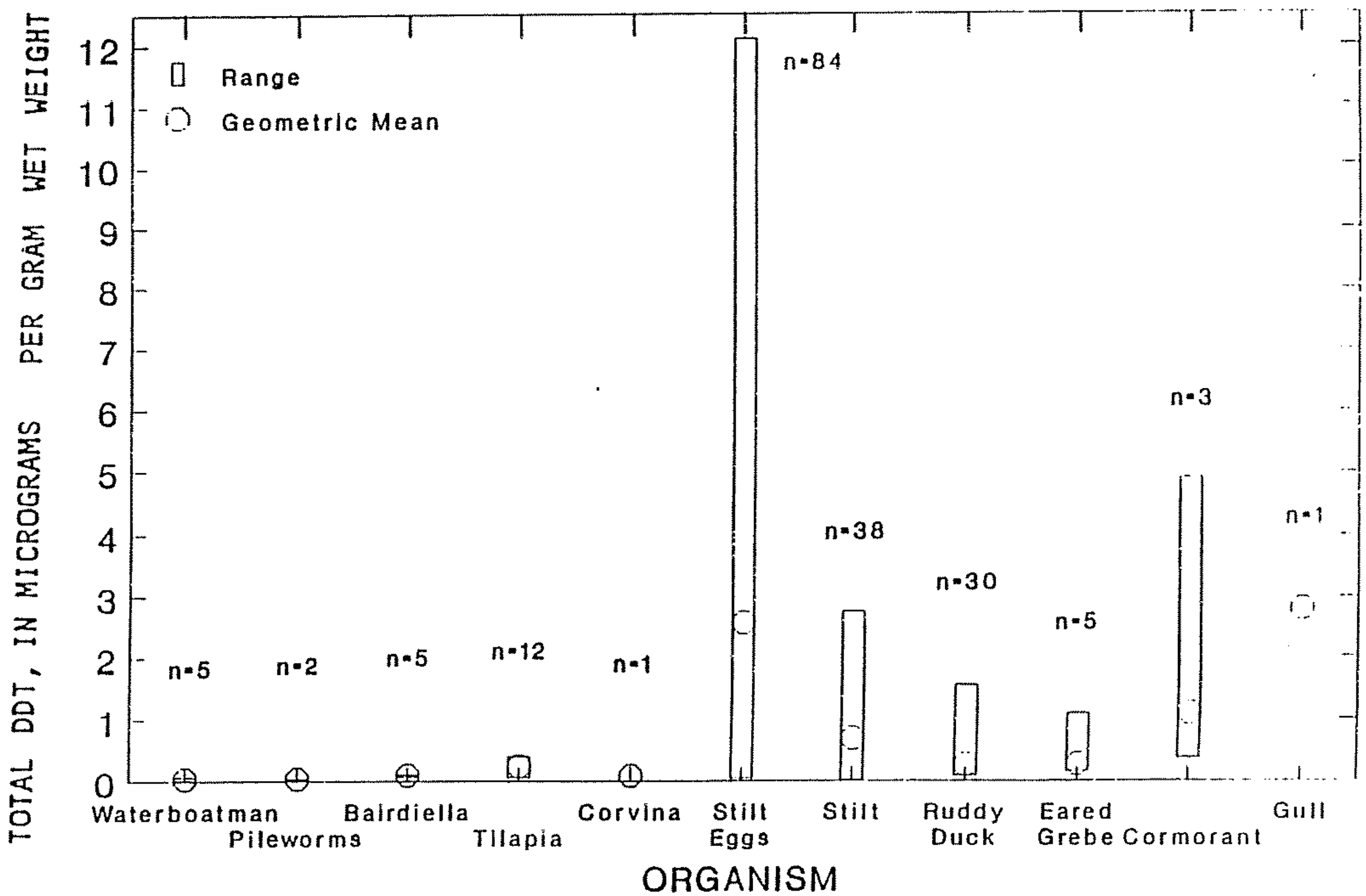


Figure 56. Total DDT concentration in food-chain organisms of the Salton Sea.

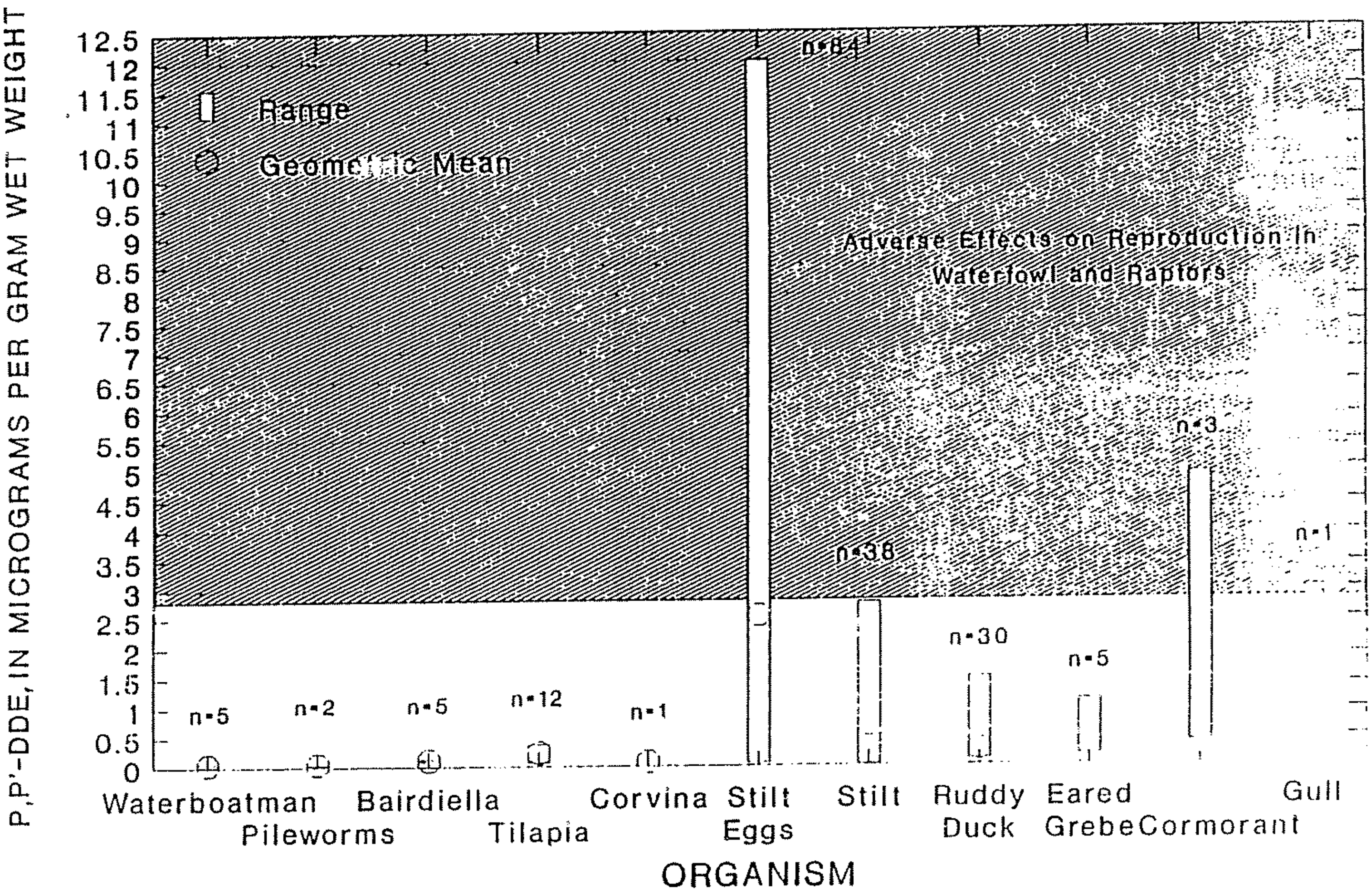


Figure 57. p,p'-DDE concentration in food-chain organisms of the Salton Sea.

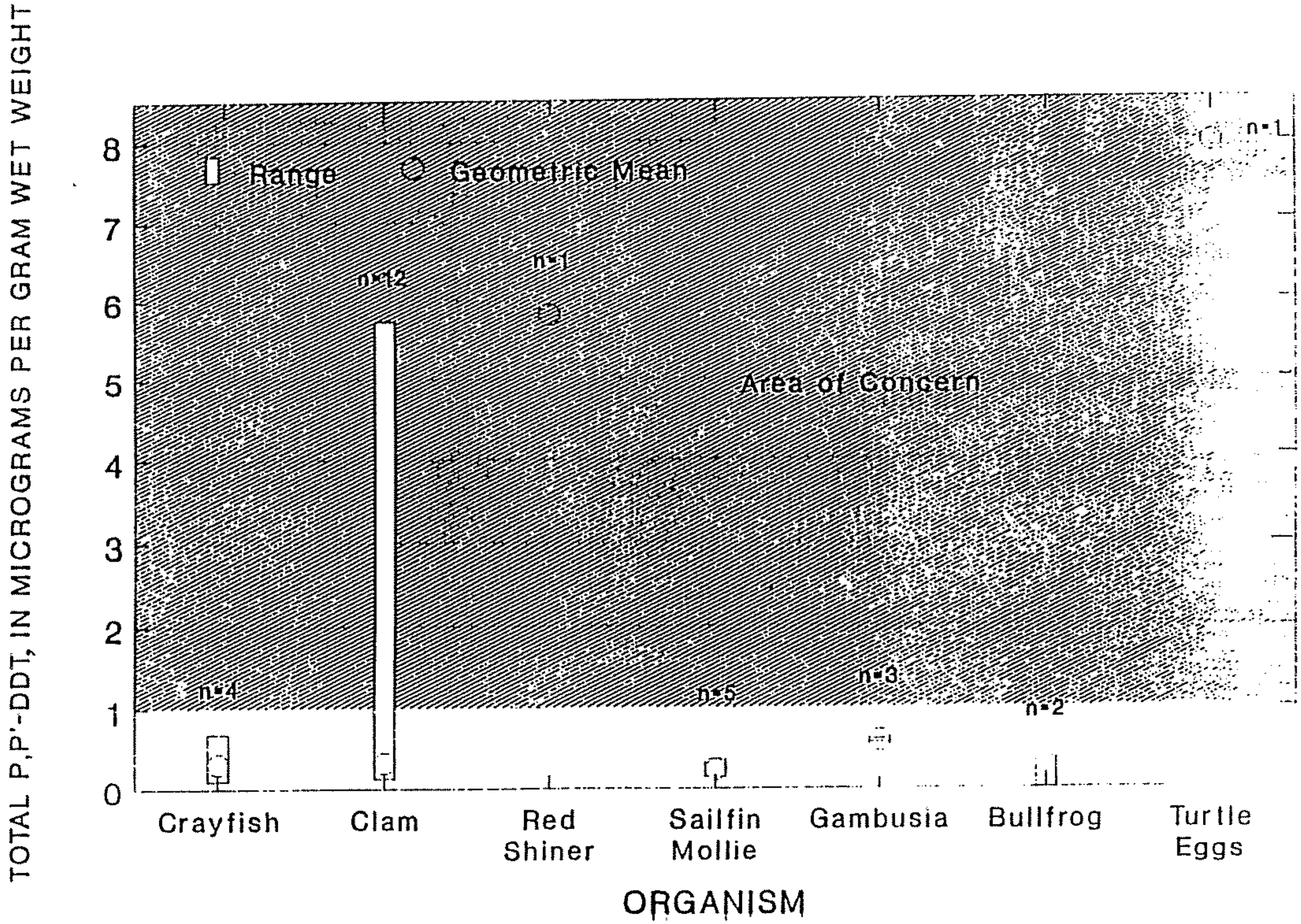


Figure 58. Total DDT concentration if food-chain organisms of rivers and drains.

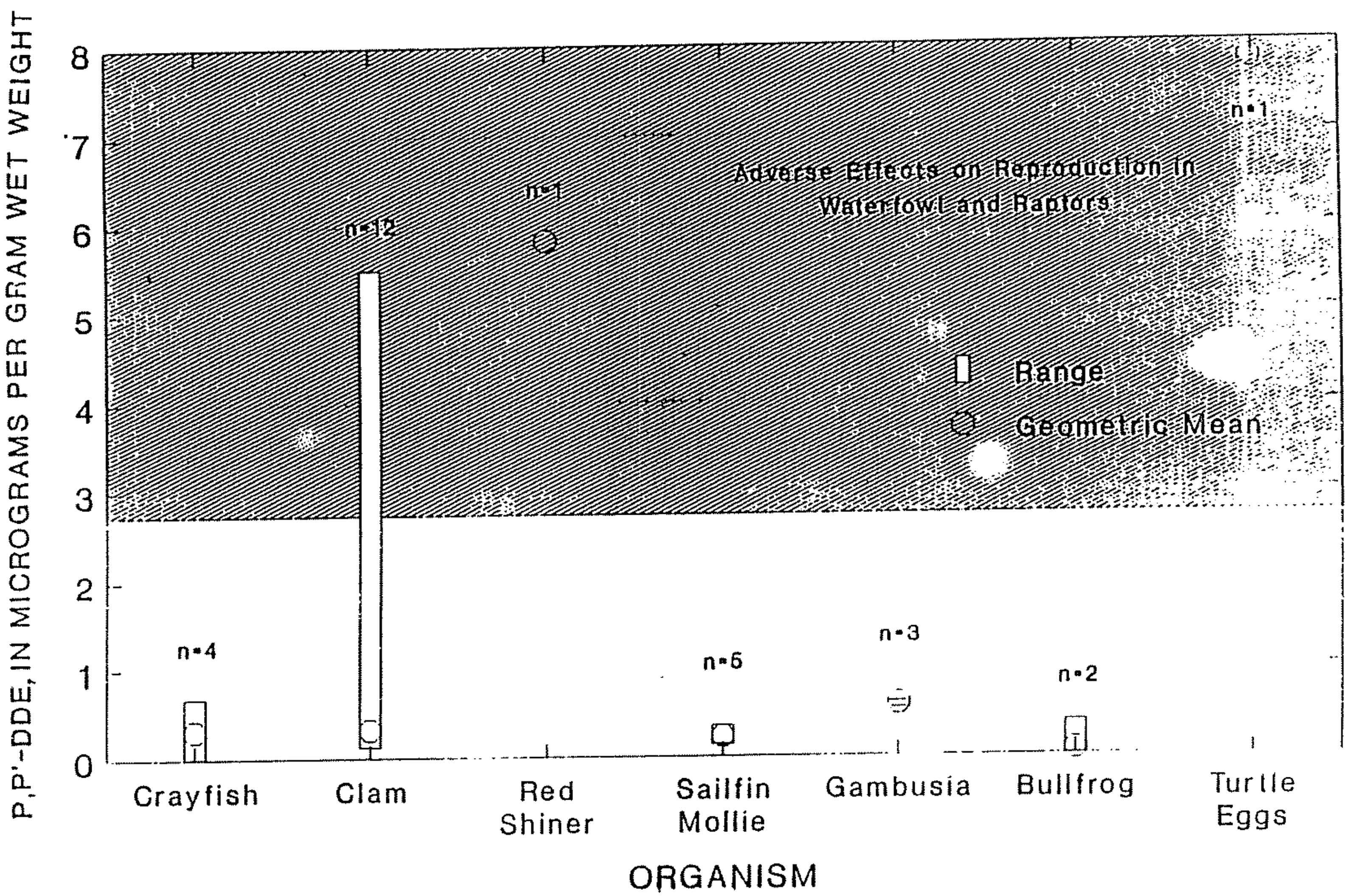


Figure 59. p,p'-DDE concentration in food-chain organisms of rivers and drains